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EFFECT OF ROTOR BLADE ROOT CUTOUT ON VERTICAL DRAG

By

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October 1970

U. S. ARMY AVIATION MATERIEL LABORATORIES
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54

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EFFECT OF ROTOR BLADE ROOT CUTOUT ON VERTICAL DRAG

Final Report

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By

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Prepared by

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ABSTRACT

Tests were conducted to determine the effect of rotor blade root cutout on the vertical drag of winged rotorcraft. Rotor thrust and torque were measured on isolated model rotors with blade root cutouts of 10 and 50 percent radius and were compared to the values obtained when a model fuselage and wings of three different planform areas were located below the rotor disc. Vertical drag was recorded on all airframe configurations with both sets of root cutout blades.

The test data revealed a decrease in vertical drag for all airframe configurations when tested with the blades having 50 percent root cutout. The largest vertical drag reduction was measured for a small wing located high on the fuselage. The 4 percent figure of merit penalty due to 50 percent blade root cutout of the isolated rotor was diminished to 2 to 3 percent for most conditions when the reduction in vertical drag was taken into consideration.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure		Page

LIST OF SYMBOLS

A	area, $in.^2$
C_D	airframe vertical drag coefficient, $D/\rho\ (\Omega R)^2 \pi R^2$
C_Q	rotor torque coefficient, $Q/\rho\ (\Omega R)^2 \pi R^3$
C_T	rotor thrust coefficient, $T/\rho\ (\Omega R)^2 \pi R^2$
c	local blade chord, in.
c_e	weighted blade chord, $\int_0^R cr^2 dr / \int_0^R r^2 dr$, in.
D	airframe vertical drag, lb
D_V	vertical drag factor, $(D-\Delta T)/(T_M-D)$
I	polar area moment of inertia, $\int r^2 dA$, $in.^4$
M	net figure of merit, $(C_T-C_D)^{3/2}/\sqrt{2}\ C_Q$
Q	rotor torque, in.-lb
R	rotor radius, in.
r	radial distance from rotor center of rotation, in.
T	rotor thrust, lb
z	distance below the rotor plane, in.
$\theta_{.75}$	collective pitch at 75 percent rotor radius, deg
ρ	air density, $slugs/ft^3$
σ	weighted rotor solidity, $bc_e/\pi R$
Ω	rotor angular velocity, rad/sec
ΔT	thrust recovery, T_M-T_R, lb

Subscripts

M	model airframe configuration
R	rotor-alone configuration
10%	10 percent root cutout rotor
50%	50 percent root cutout rotor

INTRODUCTION

Current helicopter rotor blade designs usually eliminate the aerodynamic lifting surface on the inboard 10 to 20 percent radius because of a compromise between weight and aerodynamic efficiency. The portion of the blade that is removed is referred to as root cutout. In these designs, the reduction in chord length and dynamic pressure in the root cutout region results in small changes in rotor thrust and power. This is no longer true as blade root cutout increases to values as large as 50 percent radius, as currently proposed for advanced VTOL systems such as the Sikorsky telescoping rotor system (TRAC).

The effect of blade root cutout on the hovering performance of an isolated four-bladed rotor was determined in a previous investigation[1]. It was found that a blade root cutout of 50 percent could account for a loss in hovering efficiency of 5 to 7 percent at a typical design thrust coefficient(C_T/σ = .09). Examination of airframe area causing vertical drag reveals that this area tends to be concentrated near the rotor center of rotation. This suggests that a rotor designed with a large blade root cutout may produce less vertical drag losses than a conventional rotor system since the downwash velocities near the root would be less. Thus, the difference in vertical drag may at least partially compensate for the reduction in figure of merit associated with an isolated rotor with large blade root cutout.

Several model rotor hover tests measuring the vertical drag of wing-fuselage combinations have been conducted by Sikorsky Aircraft and the United Aircraft Research Laboratories. However, all the blades utilized in these previous tests had blade root cutouts of 10 to 20 percent radius. Thus, no test data are available for rotor blades incorporating amounts of root cutout as large as 50 percent radius.

The present investigation was intended to determine experimentally the effect of blade root cutout on the vertical drag characteristics of several representative airframe models.

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1. Cassarino, S. J., EFFECT OF ROOT CUTOUT ON HOVERING PERFORMANCE, Sikorsky Aircraft Division of United Aircraft Corporation, Technical Report AFFDL-TR-70-70, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, June 1970.

TEST EQUIPMENT

MODEL ROTOR SYSTEM

The model rotor system consisted of a four-bladed rotor hub with flapping hinges but no lag hinges. Two complete sets of model rotor blades were provided. One set had blades with root cutouts of 10 percent radius and one set had blades with root cutouts of 50 percent radius. One blade of each set is shown in Figure 1. The model blades were fabricated of molded fiber glass with an NACA 0012 airfoil section over the outboard aerodynamic portion and with an elliptical spar section of about 30 percent thickness ratio over the inboard portion. The model blades were designed such that the elastic axis, center of gravity, and center of pressure were all located at the quarter chord position. They were identical to those used in a previous investigation.[2]

The model rotors had the following characteristics:

Diameter	48 inches
Number of Blades	4
Root Cutout, Percent Radius	10, 50
Weighted Solidity	.1060, .0973
Airfoil Section (Outboard)	NACA 0012
Chord	2 inches
Flapping Hinge Offset	.035R
Linear Twist (Extended to the center of rotation)	-8 degrees
Taper	None
Spar Section	30 percent ellipse
Spar Chord	.705 inch
Construction	Molded fiber glass

MODEL FUSELAGE

The model fuselage, representing a large transport compound helicopter, was a streamlined body made of mahogany with a circular cross section in the center portion, a conical tail section, and a rounded nose. The total length of the fuselage was 52.9 inches, and the diameter of the center section was 7.5 inches.

2. Ibid.

MODEL WINGS

The wings tested in this investigation, the planforms of which are shown in Figure 2, had the following characteristics:

Wing Size	Small	Medium	Large
Span	24 inches	28.5 inches	36 inches
Wing Span-Rotor Diameter Ratio	.500	.594	.750
Root Chord	7.10 inches	8.45 inches	10.66 inches
Aspect Ratio	4.5	4.5	4.5
Taper Ratio	0.5	0.5	0.5
Angle of Incidence	zero degrees	zero degrees	zero degrees

All the wings were tested in a high position on the fuselage; the small wing was also tested in a low position on the fuselage. The distance between the rotor plane and the upper surface of the wing, when mounted in the high position, was 4.3 inches, which corresponds to the scale distance taken from a full-scale compound design. The small wing, when mounted in the low position, was located at a distance of 10.7 inches below the rotor disc. The quarter chord of all model wings was directly below the center of rotation of the rotor.

Three test configurations appear in Figures 3 through 5 which show respectively the small wing in the low position on the fuselage, followed by the medium and large wings in the high position. The hollow vertical tube appearing in Figures 3 through 5 contains the vertical drag shaft on which the fuselage-wing combination is mounted. It is supported by four guy wires to prevent deflection or oscillation of the model which could be produced by the rotor downwash.

APPARATUS

The hover tests were conducted in an enclosed area, approximately 45 feet by 55 feet with a ceiling height of 40 feet, at the United Aircraft Research Laboratories. An overall view of the test rig is shown in Figure 6. A large ground board, used in previous investigations of ground effect, was located 4.5 rotor radii below the rotor thereby placing the rotor out of ground effect. A 40-horsepower, variable-speed electric motor was used as a power source. The rotor was driven through a 3:1 speed reduction system to allow operation at rotor tip speeds as high as 750 feet per second.

Average rotor thrust and torque measurements were made by means of strain-gaged load cells mounted above the rotor on a support frame. The vertical load on the fuselage-wing models was recorded independently on a

strain-gaged cell located below the ground plane. The motor balance assembly is shown schematically in Figure 7. Additional instrumentation included a solid-state counter for measuring rotor RPM, vibration meters, and a model power control console.

TEST PROCEDURES

PRETEST

Prior to testing, the thrust and vertical drag load cells were calibrated on the test rig by hanging calibration weights along their respective axes. The rig was calibrated in torque by suspending calibration weights through a known moment arm. The thrust and vertical drag, and the torque calibration slopes were determined directly in strain gage units per pound (SGU/lb) and strain gage units per inch-pound (SGU/in.-lb) respectively.

Blade tracking was checked by observation of the blade tips through a transit, with lighting supplied by a Strobotac triggered four times per revolution. Both sets of blades were statically balanced prior to installation on the rotor hub and required no additional modification for track or balance.

TEST CONFIGURATIONS

Test Model	Blade Root Cutout, Percent Radius	Distance Below the Rotor Disc, Inches
Rotor Alone	10, 50	-
Fuselage Alone	10, 50	4.3
Fuselage and Small Wing	10, 50	4.3
Fuselage and Small Wing	10, 50	10.7
Fuselage and Medium Wing	10, 50	4.3
Fuselage and Large Wing	10, 50	4.3

DATA RUNS

Each model configuration was tested at a nominal rotor tip speed of 700 feet per second and at collective pitch settings of 0, 2.5, 5.0, and 7.5 degrees, and at the highest collective pitch possible before the onset of a condition believed to be rotor blade stall flutter. The maximum value of collective pitch was 11 degrees for the 10 percent root cutout blades and 9 degrees for the 50 percent root cutout blades.

Throughout the entire test, rotor RPM was varied to maintain a blade tip Mach number equivalent to a nominal tip speed of 700 feet per second at sea level, standard day conditions. Ambient temperature and pressure were recorded for each run to determine the actual rotor tip speed and air density. Zero values of thrust, torque, and vertical drag were taken before and after each run. Collective pitch was set by means of a depth micrometer which measured the distance from a reference surface to a pin parallel to, and offset from, the blade pitch axis. This distance was

calibrated in terms of the collective pitch at the three-quarter rotor radius location.

To check the repeatability of the test data, the configuration with the large wing was tested twice using the model blades with 50 percent root cutout.

A summary of the performance data acquisition runs appears in the Appendix.

TEST DATA ACCURACY

Static data repeatability was determined from repeated calibrations of the strain gages when determining the calibration slopes discussed in the Pretest section of Test Procedures. Dynamic data repeatability was established from a previous hover test conducted during 1969. In that test, fourteen calibration runs were made on a model rotor similar to the rotors used in this investigation. The repeatability values, within two standard deviations, are listed below:

	Static Data Repeatability	Dynamic Data Repeatability
C_T/σ	$\pm$ .0001	$\pm$ .0011
C_Q/σ	$\pm$ .00006	$\pm$ .0001
C_D/σ	$\pm$ .0001	$\pm$ .0002

The estimated accuracies with which the parameters determining a given test condition could be set are as follows:

Parameter	Accuracy
z	$\pm$ .10 inch
$\theta_{.75}$	$\pm$ .20 degree
ΩR	$\pm$ 1 foot per second

DISCUSSION OF TEST RESULTS

PERFORMANCE TEST

The hovering performance characteristics of the model rotors with blade root cutouts of 10 and 50 percent radius appear in Figure 8. Thrust and torque coefficient-solidity ratios are shown for the isolated rotors and the rotor-fuselage and rotor-fuselage-wing configurations. The isolated rotor performance agrees with data obtained on similar blades in a recent investigation of blade root cutout effects on isolated rotor hover performance.[3] Throughout the present investigation, rotor thrust and torque and airframe vertical drag coefficients have been divided by the solidity of the 10 percent root cutout blades to be directly comparable in terms of actual rotor lift and power and airframe vertical drag. Figure 8 illustrates that, at a given thrust, the 50 percent root cutout blades exhibit an increase in rotor torque for all the configurations tested, resulting from the rise in profile drag associated with the elliptical spar cross section as compared to the NACA 0012 airfoil.

From Figure 8 it can be determined that, at a given torque, increasingly higher values of rotor thrust are measured as the fuselage and wings of larger planform area are added to either rotor. The difference in the measured thrusts is referred to as thrust recovery, ΔT, and is similar in nature to the ground effect experienced when a helicopter rotor is hovering in the vicinity of the ground. Thus, the presence of the fuselage and wings acts as a partial ground, affecting the rotor downwash.

The variation of airframe vertical drag with rotor torque is presented in Figure 9 for the five configurations tested with the 10 and 50 percent root cutout blades. Figure 9 reveals that, at any rotor torque level, the airframe vertical drag increases as wings of larger planform area are added to the fuselage. The result is expected since the airframe vertical drag is related to the projected area of the fuselage-wing combination. In addition, the small wing mounted in the low position on the fuselage exhibits a larger vertical drag than the same wing in the high position due to the higher downwash velocity at a greater distance from the rotor plane. For any test configuration, the blades with 50 percent root cutout produce a lower vertical drag than that measured with the blades with 10 percent root cutout.

Rotor thrust and vertical drag were presented as functions of rotor torque in Figures 8 and 9 respectively to permit comparison at constant power. However, in the following presentation, the nondimensional quantity, $(C_T-C_D)/\sigma_{10\%}$, which will be referred to as the net thrust coefficient-solidity ratio, is utilized instead of $C_T/\sigma_{10\%}$. The net thrust coefficient-solidity ratio is proportional to the aircraft gross weight, with values on the order of .070 to .090 being typical of design conditions. The variations of net thrust with rotor torque and airframe

3. Ibid.

vertical drag are presented in Figures 10 and 11 respectively. Figure 10 is in a form similar to Figure 8. The results of Figure 11 show that, for net thrust values greater than .020, the airframe vertical drag varies almost linearly with net thrust for all configurations tested.

The thrust recovery-thrust ratio, $\Delta T/T_M$, which is a measure of the percent increase in thrust resulting from the partial ground effect of the fuselage and the fuselage-wing combinations, is presented as a function of net thrust in Figures 12(a) and (b) for blade root cutouts of 10 and 50 percent respectively. Figure 12(a) shows that, at the highest net thrust measured for each configuration, the increase in thrust for 10 percent blade root cutout ranges between 3 and 7 percent as the planform area of the wings is increased. This behavior is expected since the larger wings should produce more ground effect than the smaller wings. For the 50 percent root cutout blades, the thrust recovery-thrust ratio ranges from 1 to 3 percent for all configurations at the highest measured net thrust.

A comparison of Figures 12(a) and (b) reveals that the effect of blade root cutout is to decrease the thrust recovery-thrust ratio at any net thrust level for all test configurations except the fuselage alone, which shows little difference throughout the net thrust range. The loss in thrust recovery associated with the 50 percent root cutout blades may be attributed to the reduced downwash in the root cutout region, which in turn diminishes the partial ground effect. Locating the small wing high on the fuselage results in a small increase in thrust throughout the net thrust range for the 50 percent root cutout blades, as seen in Figure 12(b). However, for the 10 percent root cutout blades, Figure 12(a) shows that, within experimental accuracy, no difference in thrust recovery-thrust ratio is measured for the small wing in the high or low position on the fuselage.

The ratio of the thrust recovery to the airframe vertical drag, $\Delta T/D$, is illustrated in Figures 13(a) and (b) for the blades with 10 and 50 percent root cutout respectively. At a design net thrust, $(C_T-C_D)/\sigma_{10\%}$ = .070 to .090, the thrust recovery-vertical drag ratio is about 30 to 50 percent for the 10 percent root cutout blades while for the 50 percent root cutout blades it ranges from 20 to 50 percent. The largest values are measured for the fuselage and the small high wing, while the medium wing exhibits the lowest values.

A parameter used in the presentation of vertical drag data is the ratio of the airframe vertical drag to the rotor thrust, D/T_M. This ratio is presented as a function of net thrust in Figures 14(a) and (b) for blade root cutouts of 10 and 50 percent respectively. Figure 14 shows that the vertical drag-thrust ratio decreases slightly with increasing thrust levels for all configurations tested with both blade root cutout values. This effect is greatest for the configurations with the largest planform areas. A comparison of Figures 14(a) and (b) shows that an increase in blade root cutout from 10 to 50 percent diminishes the D/T_M ratio for all configurations throughout the measured net thrust level.

The most important parameter used in vertical drag analyses is the vertical

drag factor, D_V, which is defined as the difference between the airframe vertical drag and the thrust recovery, divided by the net thrust. The vertical drag factor is a measure of how much of the hover thrust is needed to overcome the vertical drag due to the presence of the aircraft in the rotor wake. Consequently, a reduction in the vertical drag factor may result in significant improvements in rotor hovering efficiency.

Figures 15(a) and (b) present the variation of vertical drag factor with rotor net thrust for blade root cutout values of 10 and 50 percent respectively. From these figures it can be seen that, for both sets of root cutout rotors, addition of wings of increasing planform area results in higher values of the vertical drag factor. At the highest measured net thrust, D_V values greater than 14 percent are measured for the large wing with both blade root cutout values. Although the thrust recovery is generally greater for the bigger wings, it does not offset the corresponding large increase in vertical drag. Figure 15 also illustrates that the vertical drag factor does not depend significantly on the net thrust level for the fuselage or the small wing. The medium and large wings, however, demonstrate significant variations of D_V with net thrust. From Figure 15 it can be seen that, for both rotors, the small high wing has a lower vertical drag factor than the same wing in the low position on the fuselage.

To relate the effect of blade root cutout to the vertical drag factor, the ratio of the vertical drag factor for the 50 percent root cutout blades to that of the 10 percent root cutout blades is presented in Figure 16 as a function of net thrust. This figure shows that the 50 percent root cutout blades produce less vertical drag than the 10 percent root cutout blades for all the configurations tested. The percent reduction in D_V is greatest at the lower net thrust levels for all the fuselage-wing combinations. The small wing mounted high on the fuselage exhibits the largest percent reduction in vertical drag factor throughout the net thrust range. This reduction is 31 percent at a net thrust coefficient-solidity ratio of .080 as compared to 14 percent measured for the same wing in the low position on the fuselage. As the wing planform area increases, the beneficial effect of blade root cutout diminishes to 9 percent for the medium wing at a net thrust coefficient-solidity ratio of .080 and 3 percent for the large wing at a net thrust coefficient-solidity ratio of .075.

A previous investigation[4] utilizing similar blades showed that, at a typical design thrust coefficient (C_T/σ = .09), a loss in isolated rotor figure of merit of 5 to 7 percent resulted from 50 percent blade root cutout. Addition of an airframe below the rotor disc further reduces the hovering performance since the rotor must produce an additional thrust to overcome the vertical drag of the airframe. However, since the measured vertical drag is less for rotor blades with 50 percent root cutout, then the net loss in the figure of merit due specifically to large values of blade root cutout should be diminished.

4. Ibid.

A plot of net figure of merit versus net thrust is presented in Figure 17(a) for a blade root cutout of 10 percent and in Figure 17(b) for the 50 percent root cutout blades. The figure of merit of the isolated rotors is included for comparison purposes. Figure 17 shows a reduction in net figure of merit at any net thrust for all airframe configurations when compared to the rotor-alone configuration. Also, it can be observed that, for both rotors, the small wing located high on the fuselage exhibits a higher net hovering efficiency than the same wing mounted low on the fuselage, resulting from the lower vertical drag factor discussed previously.

The ratio of the net figure of merit of the 50 percent blade root cutout rotor to that of the 10 percent blade root cutout rotor is presented in Figure 18 as a function of net thrust for all the configurations tested. This figure demonstrates that, when vertical drag is considered, the hovering penalty associated with a 50 percent blade root cutout is less for all airframe configurations than that for the rotor-alone configuration. The improvement in hovering efficiency associated with the 50 percent blade root cutout rotor is greater at higher net thrust levels, $(C_T-C_D)/\sigma_{10\%}=.070$ to .080, for all configurations tested except the large wing. At the highest measured net thrust value of .080, the loss in hovering performance due to a 50 percent blade root cutout can be reduced from over 4 percent for the rotor-alone configuration to 2 percent for the small wing located high on the fuselage. A comparison of the results presented in Figure 18 for the small wing configurations indicates that the location of the wing on the fuselage is important, since the small high wing has a hovering efficiency about 1 percent higher than the low wing configuration at a net thrust coefficient-solidity ratio of .080.

CORRELATION OF TEST RESULTS

Several methods have been utilized in the past to correlate vertical drag experimental results with analytical calculations. Two common techniques are the blocked area ratio method and the polar area moment of inertia ratio method.

The blocked area ratio method compares the airframe area in the contracted rotor wake to the measured vertical drag. The assumption is made that, at a given distance below the rotor plane, the radial distribution of downwash is constant in the rotor wake. This constant downwash distribution would be produced by a rotor having blades with an "ideal twist", i.e., a twist inversely proportional to the distance from the center of rotation.

The polar area moment of inertia ratio method assumes a triangular radial distribution of the downwash velocity in the contracted rotor wake, an assumption supported by experimental measurements. Thus, the slipstream dynamic pressure is a function of the radial distance squared. The vertical drag distribution of a given airframe segment then increases parabolically with its distance from the center of rotation. The area of the airframe segment is weighted accordingly by use of the polar area moment of inertia about the rotor hub.

The blocked area ratio and polar area moment of inertia ratio are utilized in the correlation of vertical drag results in this investigation. These ratios are defined as the blocked area and the polar area moment of that portion of the airframe within the contracted rotor wake divided, respectively, by the rotor disc area (πR^2) and the rotor polar area moment ($\pi R^4/2$). The wake contraction was determined from a previous study[5] at a typical design thrust condition (C_T/σ = .09). For a blade root cutout of 10 percent, a ratio of contracted wake radius to rotor radius of .85 was used for the fuselage and the high-mounted wings, while the low-mounted wing had a contraction ratio of .80. For the 50 percent root cutout blades, contraction ratios of .87 and .82 were utilized respectively.

The values of the blocked area ratio and polar area moment of inertia ratio for all the test configurations are summarized in Figure 19. This figure shows that, as the wing planform area increases, the blocked area ratio and the polar area moment ratio increase at different rates since the blocked area is not related to the distance from the center of rotation while the polar area moment is proportional to the distance squared. For all airframe configurations, the 50 percent root cutout blades result in higher values of blocked area ratio and polar area moment ratio due to slightly larger values of contracted wake radius utilized for these blades. While all of the wings are within the rotor wake, the fuselage extends to 110 percent of the rotor diameter. Thus, the larger contraction ratios associated with the 50 percent root cutout blades exposes more of the fuselage area to the downwash field with a resulting increase in the blocked area ratio and the polar area moment ratio. No allowance has been made for the reduced downwash produced in the root cutout region. The high and low mounting positions of the small wing give the same values of blocked area ratio and polar area moment ratio since all of the wing lies in the contracted wake for both positions.

The vertical drag-thrust ratio is presented in Figures 20 and 21 as a function of blocked area ratio and polar area moment of inertia ratio, respectively, for two net thrust levels: $(C_T-C_D)/\sigma_{10\%}$ = .050 and .075. The two methods produce nonlinear variations of the vertical drag-thrust ratio for both sets of root cutout rotors.

The vertical drag factor, which includes thrust recovery, is correlated with the blocked area ratio and the polar area moment ratio in Figures 22 and 23 respectively. These figures show that at a net thrust coefficient-solidity ratio of .075 (which is typical of design conditions), the vertical drag factor correlation is better than the correlation shown in Figures 20 and 21 for the vertical drag-thrust ratio for blade root cutouts of 10 and 50 percent radius. Therefore, it may be concluded that correlation is improved when thrust recovery is accounted for. However, both analytical techniques produce nonlinear variations of the vertical drag factor. The highly nonlinear behavior of the 50 percent root cutout blades is suggested by the angle of attack distribution along the blade

5. Ibid.

which exhibits severe distortions in the root cutout region and near the blade tip.[6] Thus, representation of the downwash profile across the rotor wake by a constant value or a linear distribution is not valid for the blades with 50 percent root cutout. It is concluded that the blocked area ratio and the polar area moment of inertia ratio methods are of limited use in estimating the vertical drag penalties of winged rotorcraft, especially for a rotor system incorporating large values of blade root cutout.

TEST DATA REPEATABILITY

The large wing was retested using the model blades with 50 percent root cutout to check the test data repeatability. Rotor thrust and torque and airframe vertical drag data were measured at collective pitch values of 0, 2.5, 5.0, 7.5, and 9 degrees at a nominal rotor tip speed of 700 feet per second. The results are presented in Figure 24, which shows measured values of thrust and vertical drag versus rotor torque. This figure illustrates that, within experimental accuracy, the test data agreed for the two sets of runs.

6. Ibid.

CONCLUSIONS

The conclusions derived from this investigation may be summarized as follows:

1. The vertical drag factor measured for a typical compound helicopter configuration is lower for rotor blades with 50 percent root cutout than for blades with 10 percent root cutout. At a typical design net thrust coefficient-solidity ratio of .080, the largest reduction, as much as 31 percent, occurs for a small wing located high on the fuselage.

2. The influence of blade root cutout on the vertical drag factor is increased with a decrease in net thrust and reduced with an increase in wing planform area or distance from the rotor disc.

3. For 10 and 50 percent blade root cutouts, the vertical drag factor increases with airframe area and with distance from the rotor plane.

4. A loss in hovering efficiency greater than 4 percent is measured for the isolated rotor with 50 percent blade root cutout. When the airframe vertical drag associated with the 50 percent root cutout blades is accounted for, the performance deficiency in terms of the net figure of merit decreases to 2 to 3 percent for most configurations at a net thrust coefficient-solidity ratio of .080.

5. The thrust recovery resulting from the partial ground effect of an airframe within the wake of a hovering rotor increases as the size of the airframe increases. The thrust recovery measured for blades with 50 percent root cutout is less than that for 10 percent root cutout blades for the same model configuration and net thrust coefficient.

6. The ratio of the thrust recovery to vertical drag depends on the blade root cutout value and the airframe configuration, but generally it varies between 20 and 50 percent.

7. The blocked area ratio and the polar area moment of inertia ratio methods are of limited use in predicting vertical drag, especially for a rotor system with large root cutout blades.

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4. A loss in hovering efficiency greater than 4 percent is measured for the isolated rotor with 50 percent blade root cutout. When the airframe vertical drag associated with the 50 percent root cutout blades is accounted for, the performance deficiency in terms of the net figure of merit decreases to 2 to 3 percent for most configurations at a net thrust coefficient-solidity ratio of .080.

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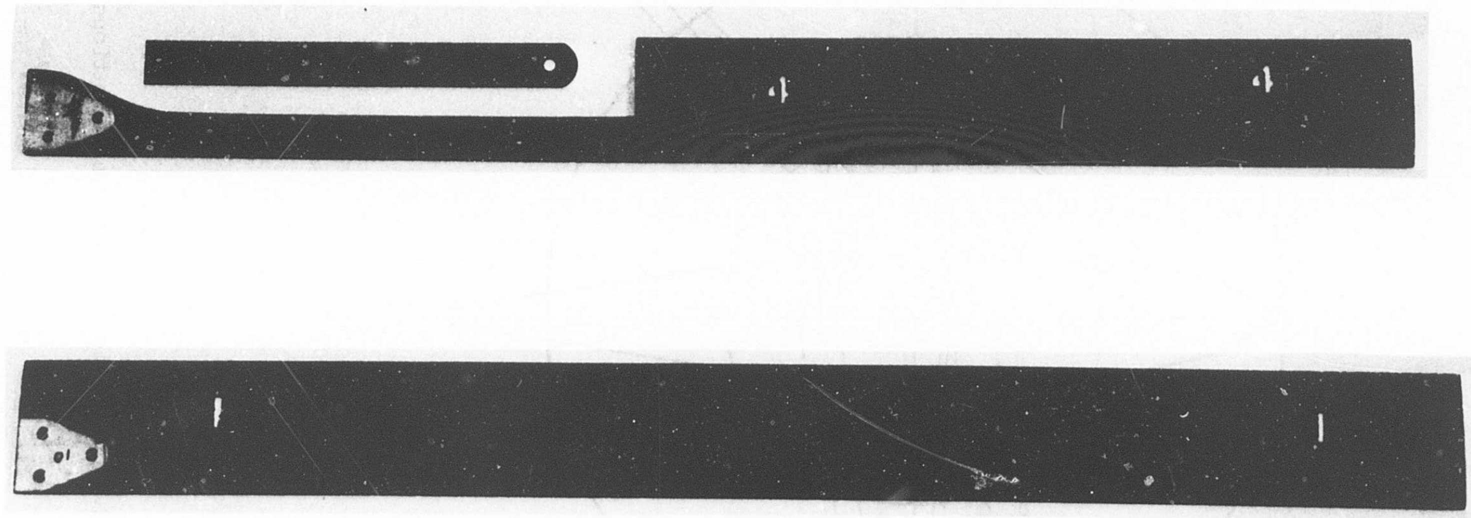


Figure 1. Root Cutout Test Blades.

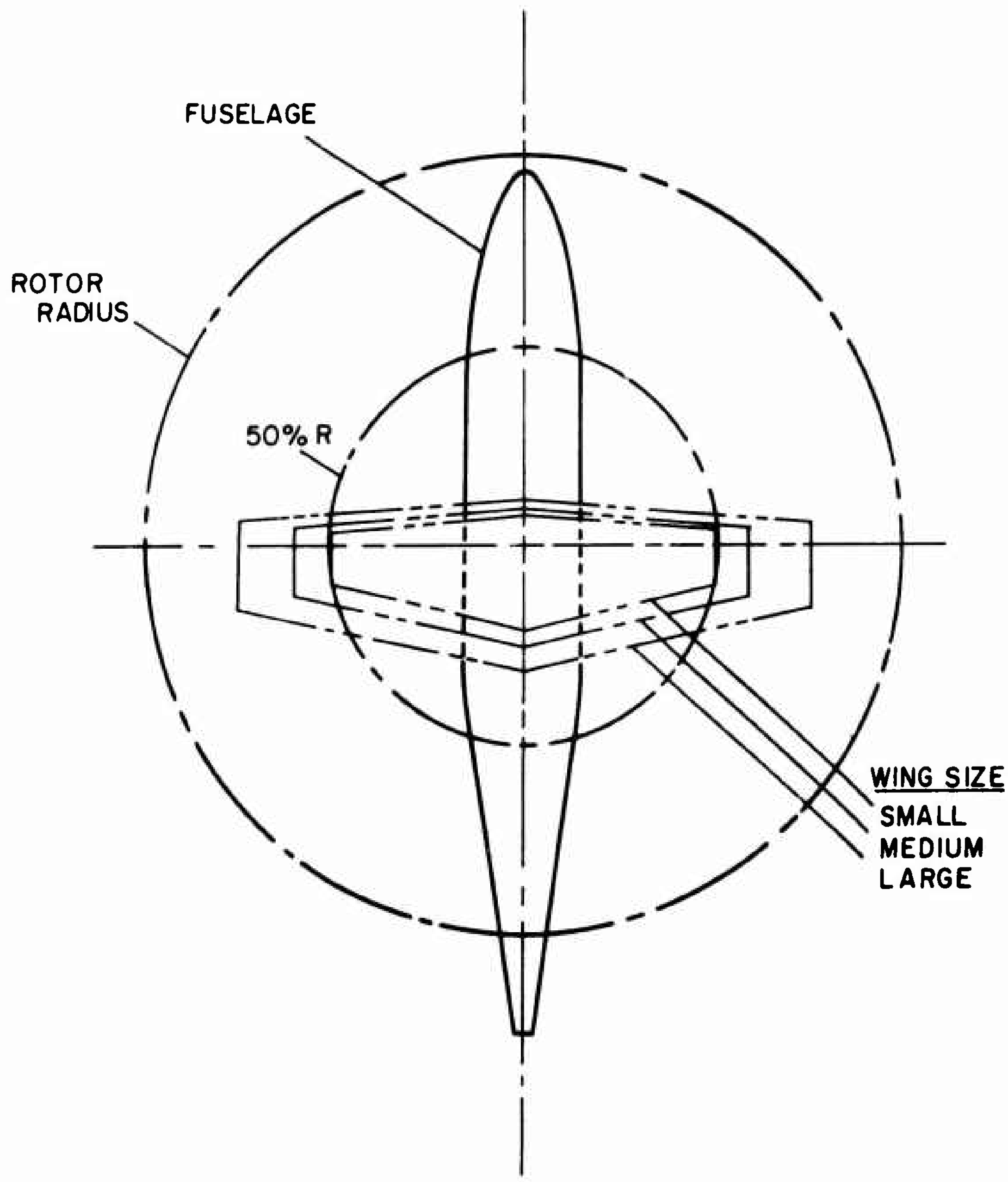


Figure 2. Schematic of Test Configurations.

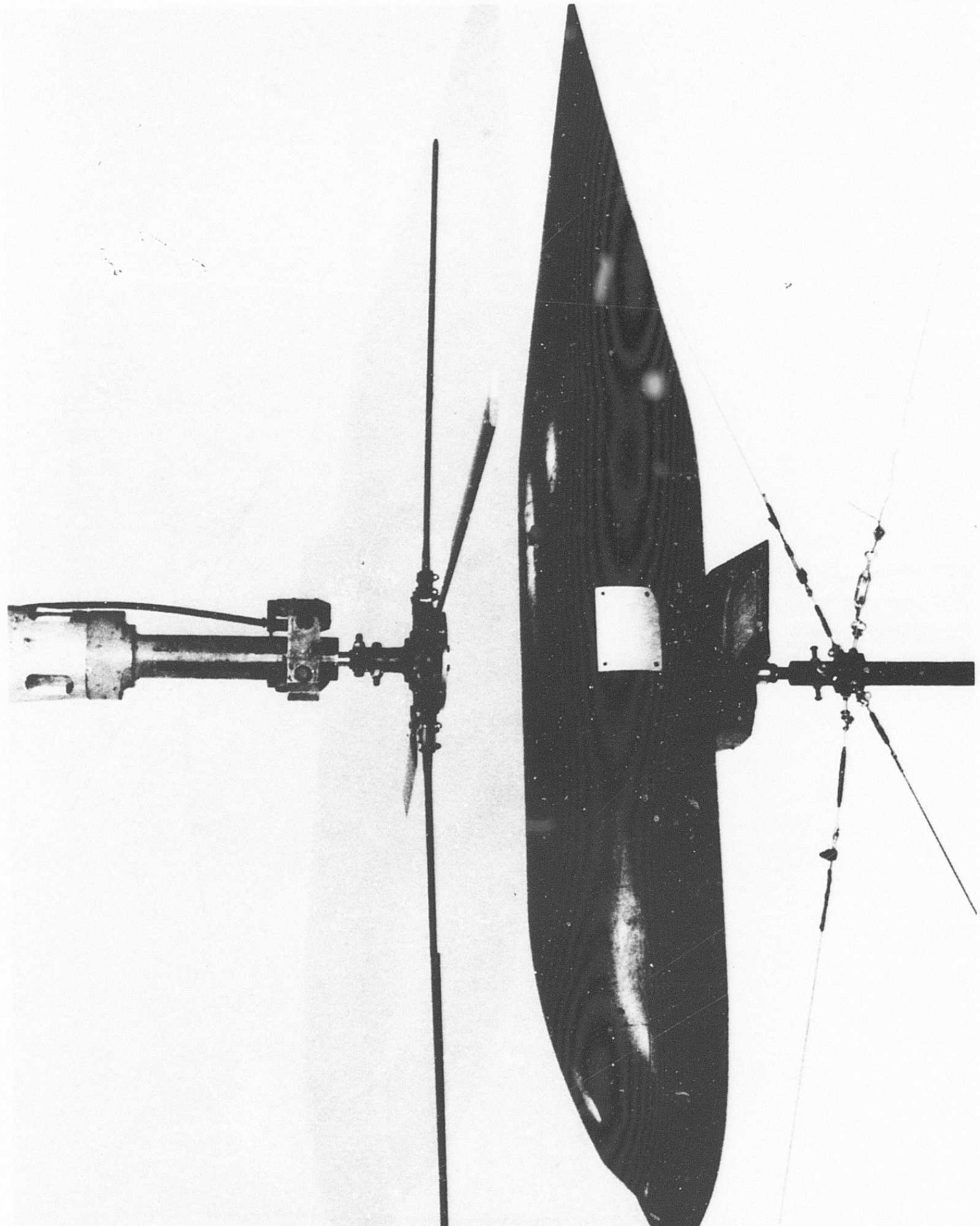


Figure 3. Model Configuration; Small Wing in the Low Position.

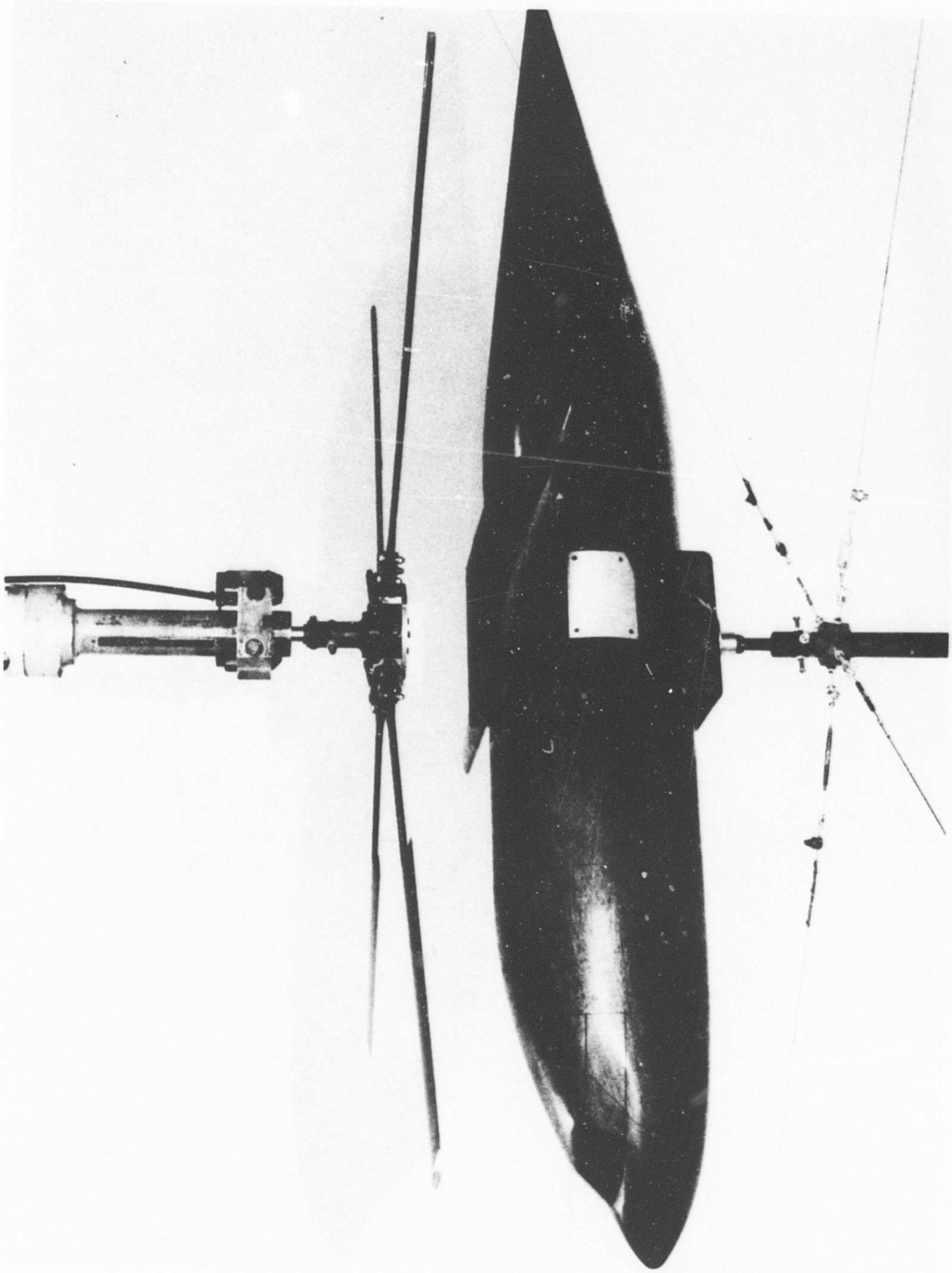


Figure 4. Model Configuration; Medium Wing in the High Position.

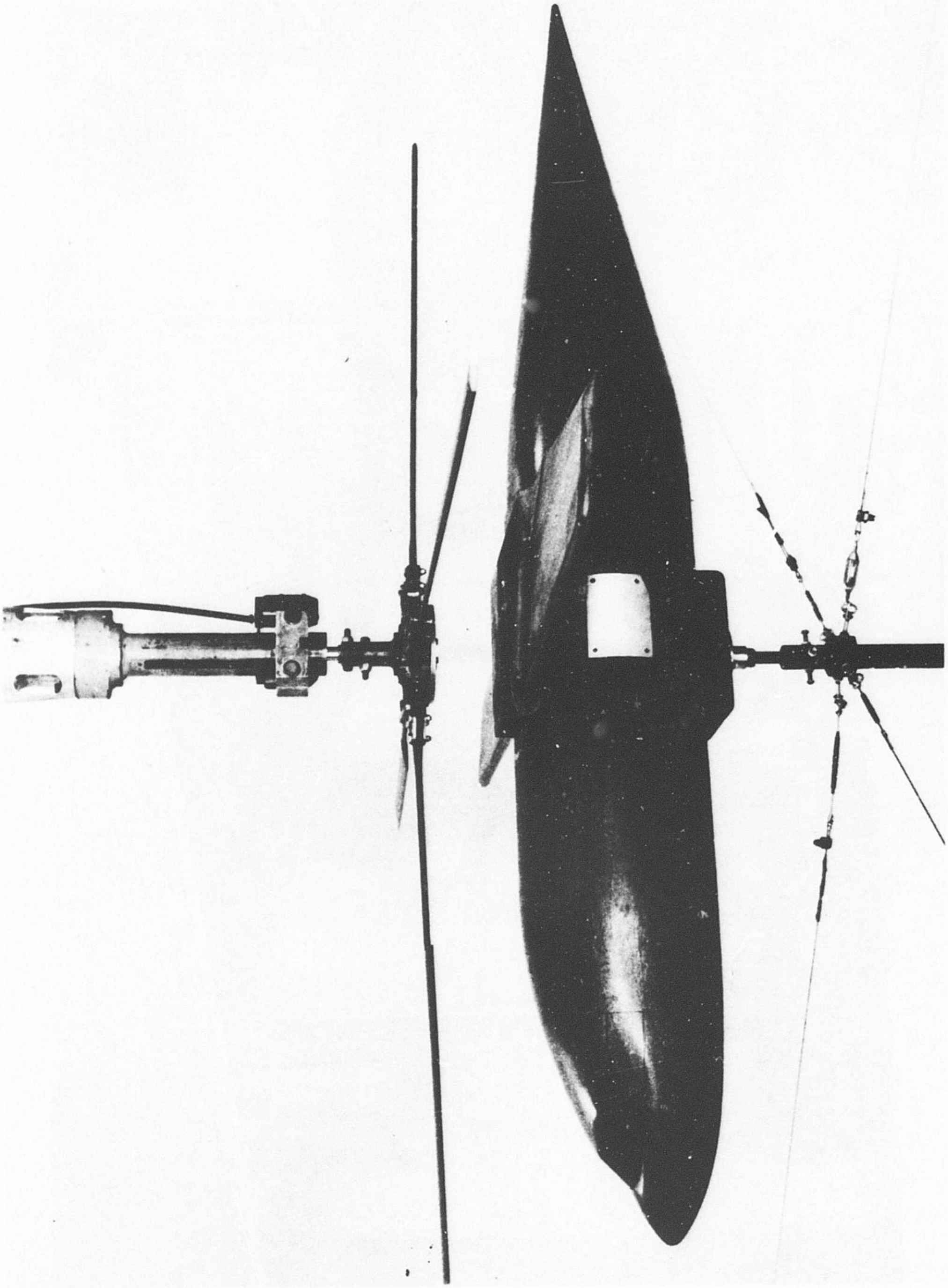


Figure 5. Model Configuration; Large Wing in the High Position.

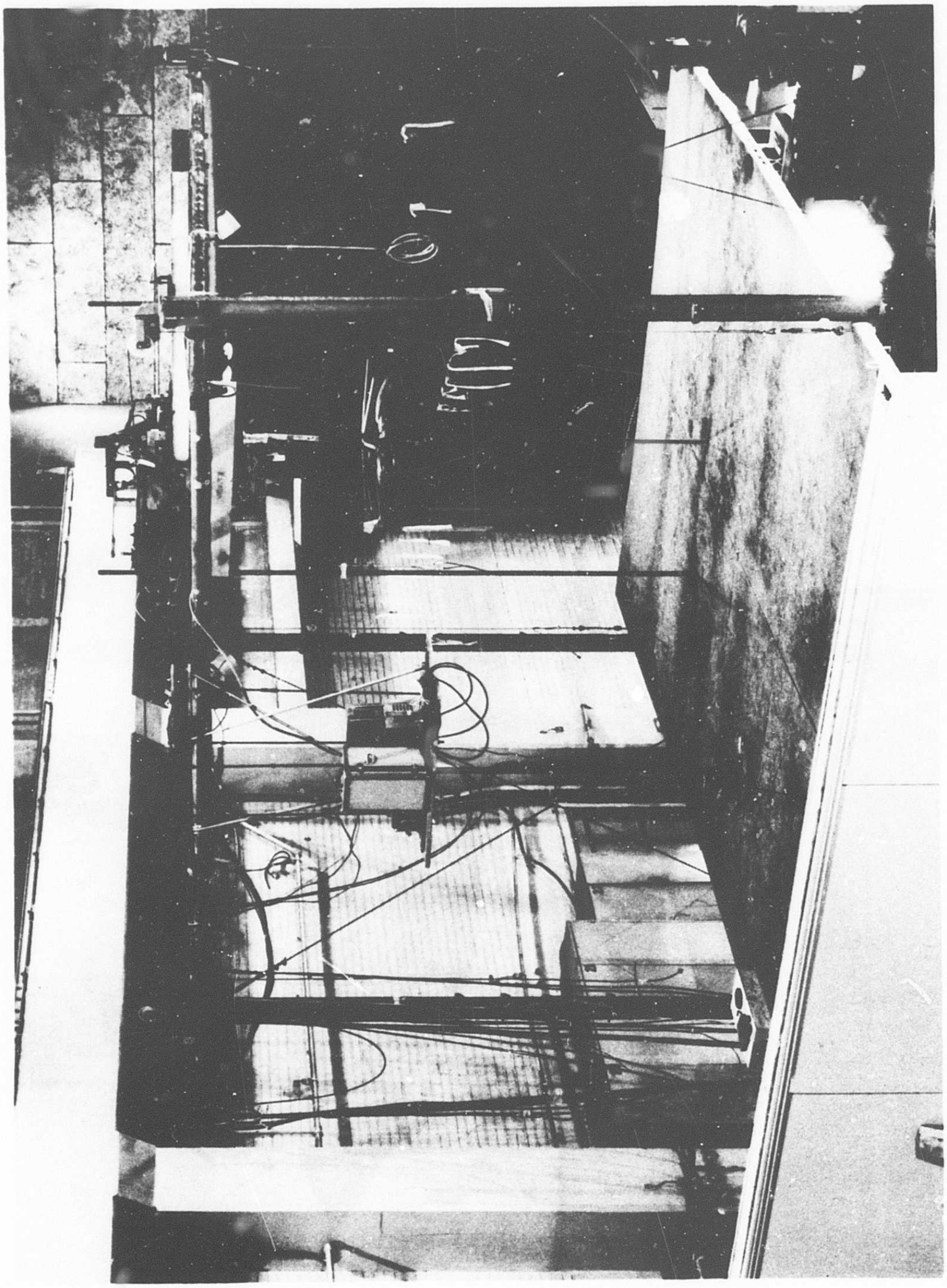


Figure 6. 40-Horsepower Hover and Vertical Drag Test Stand.

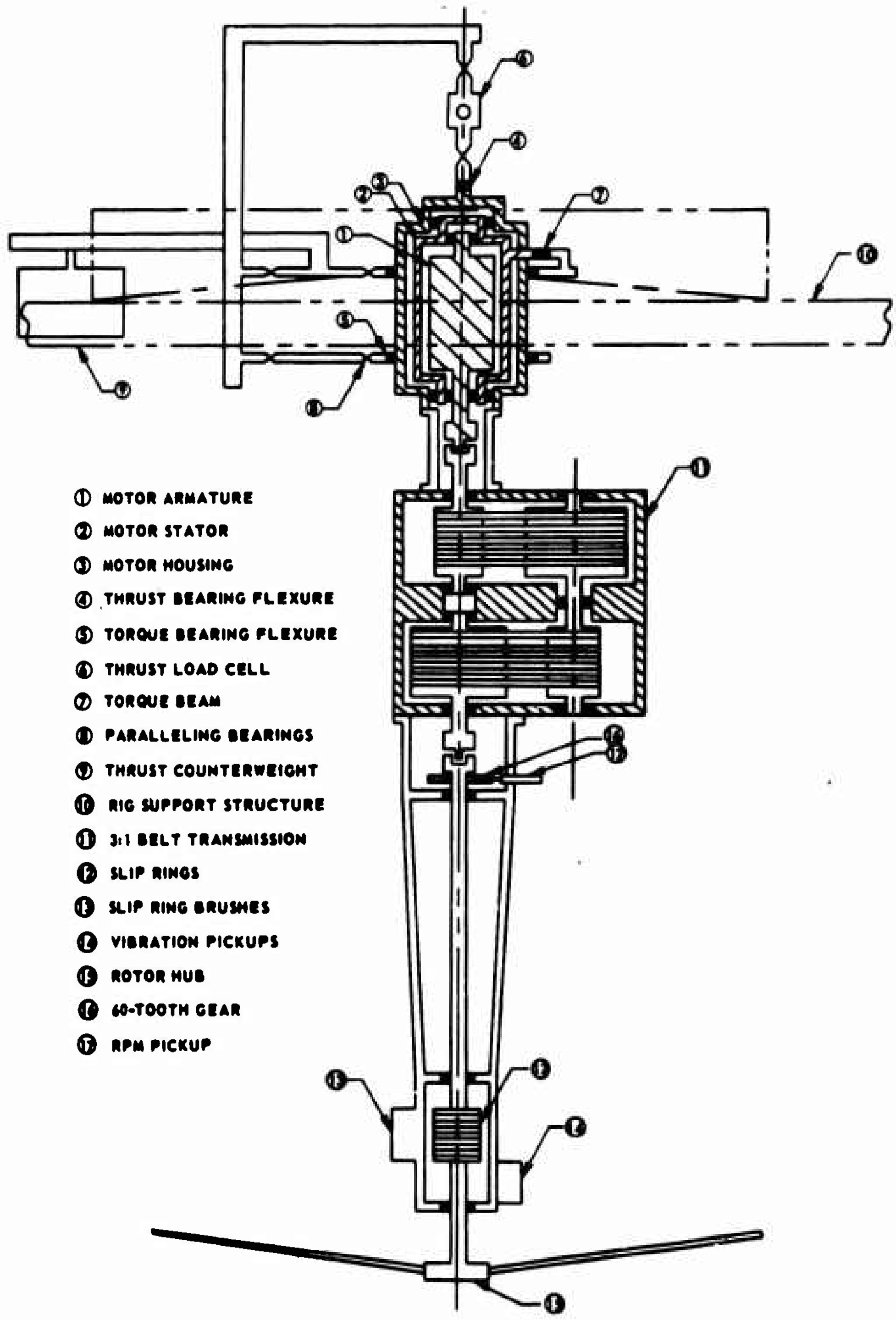
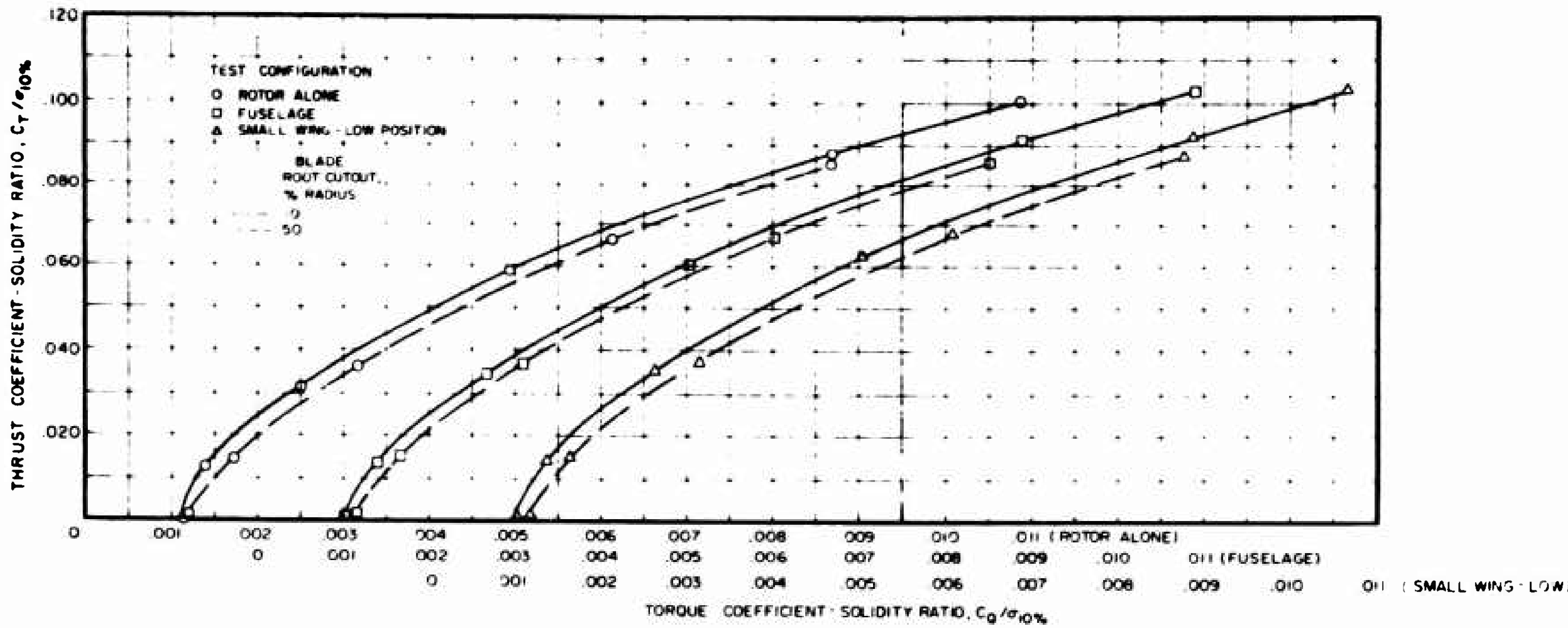
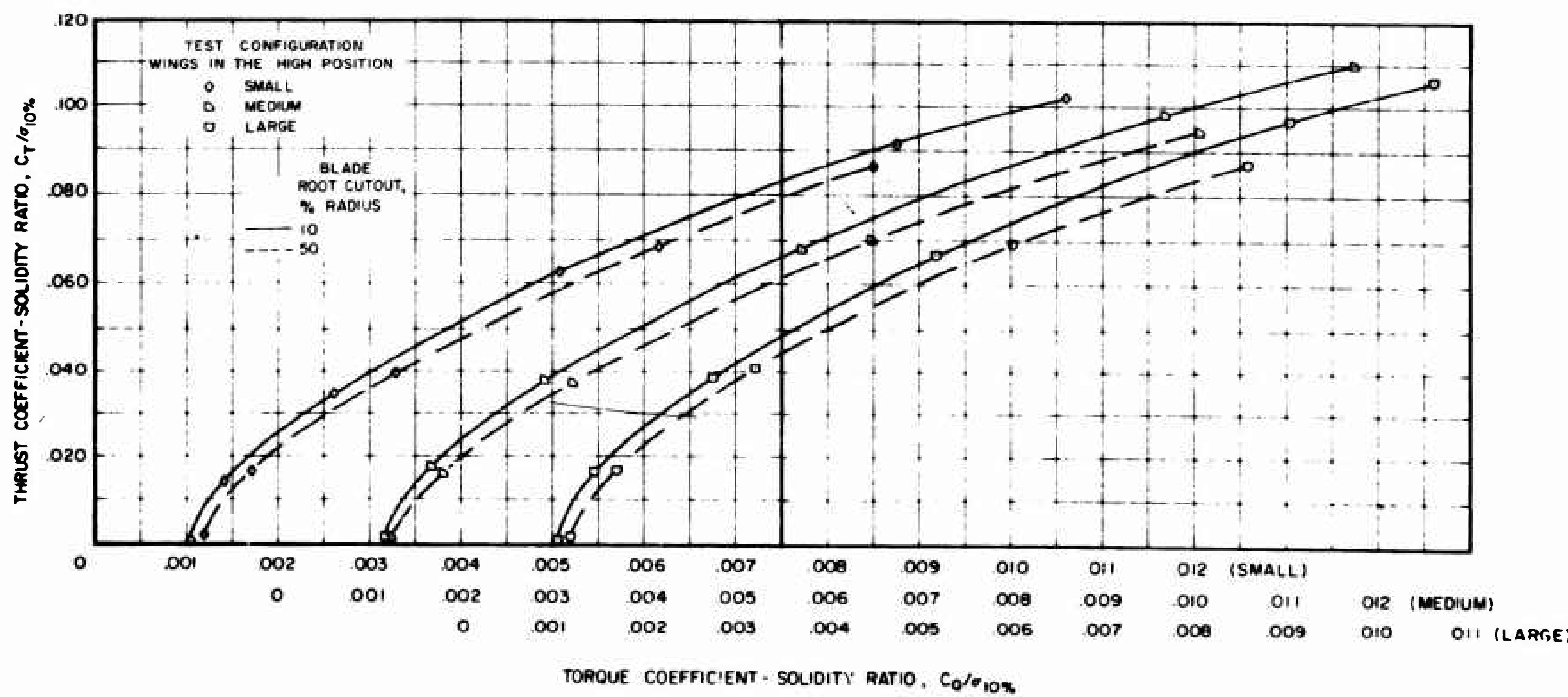


Figure 7. Model Rotor Balance Assembly.



(a) ROTOR ALONE, FUSELAGE, AND SMALL WING IN THE LOW POSITION

Figure 8. Variation of Rotor Thrust With Torque.



(b) SMALL, MEDIUM, AND LARGE WING, IN HIGH POSITION

Figure 8. Concluded.

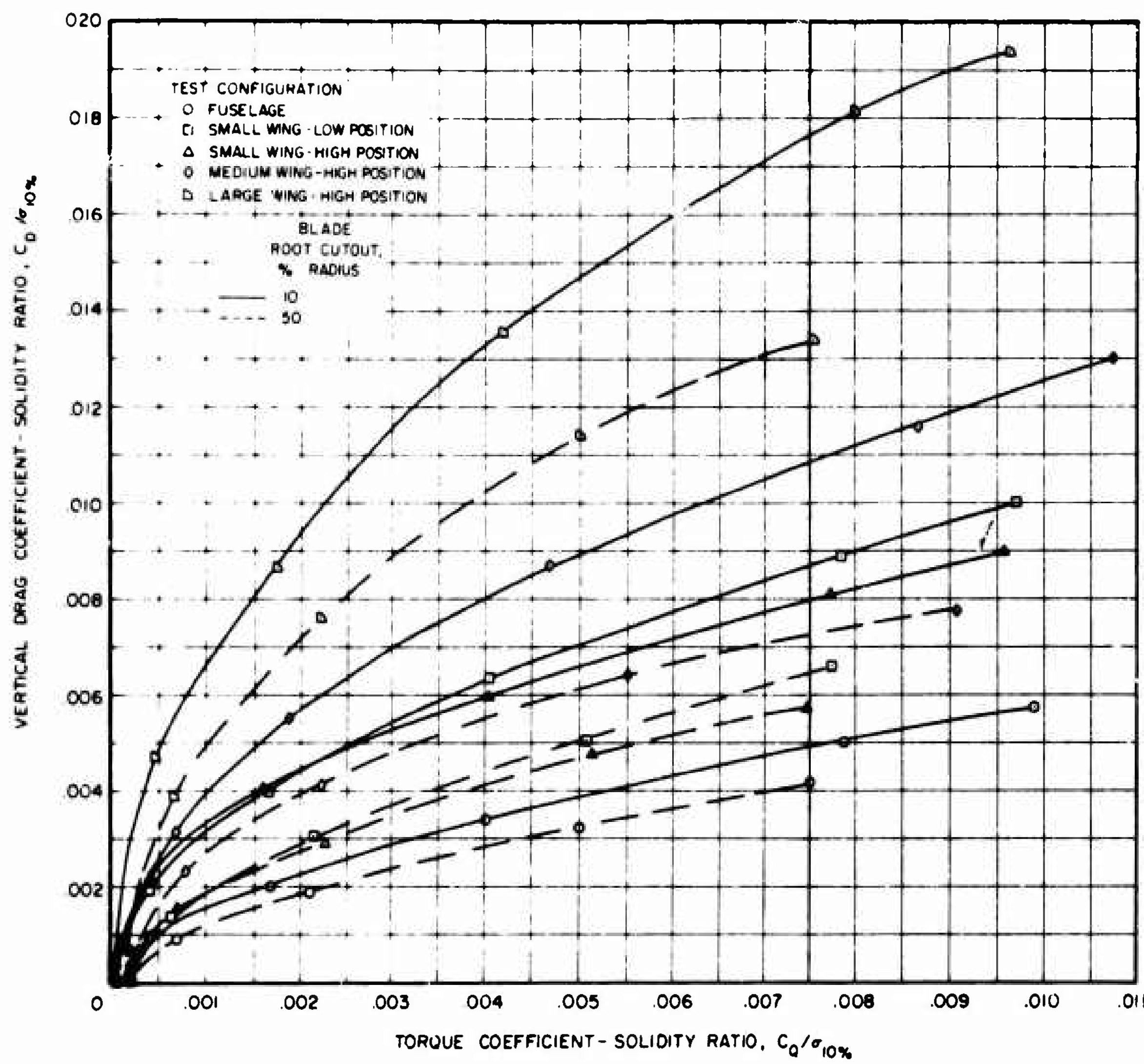


Figure 9. Variation of Airframe Vertical Drag With Rotor Torque.

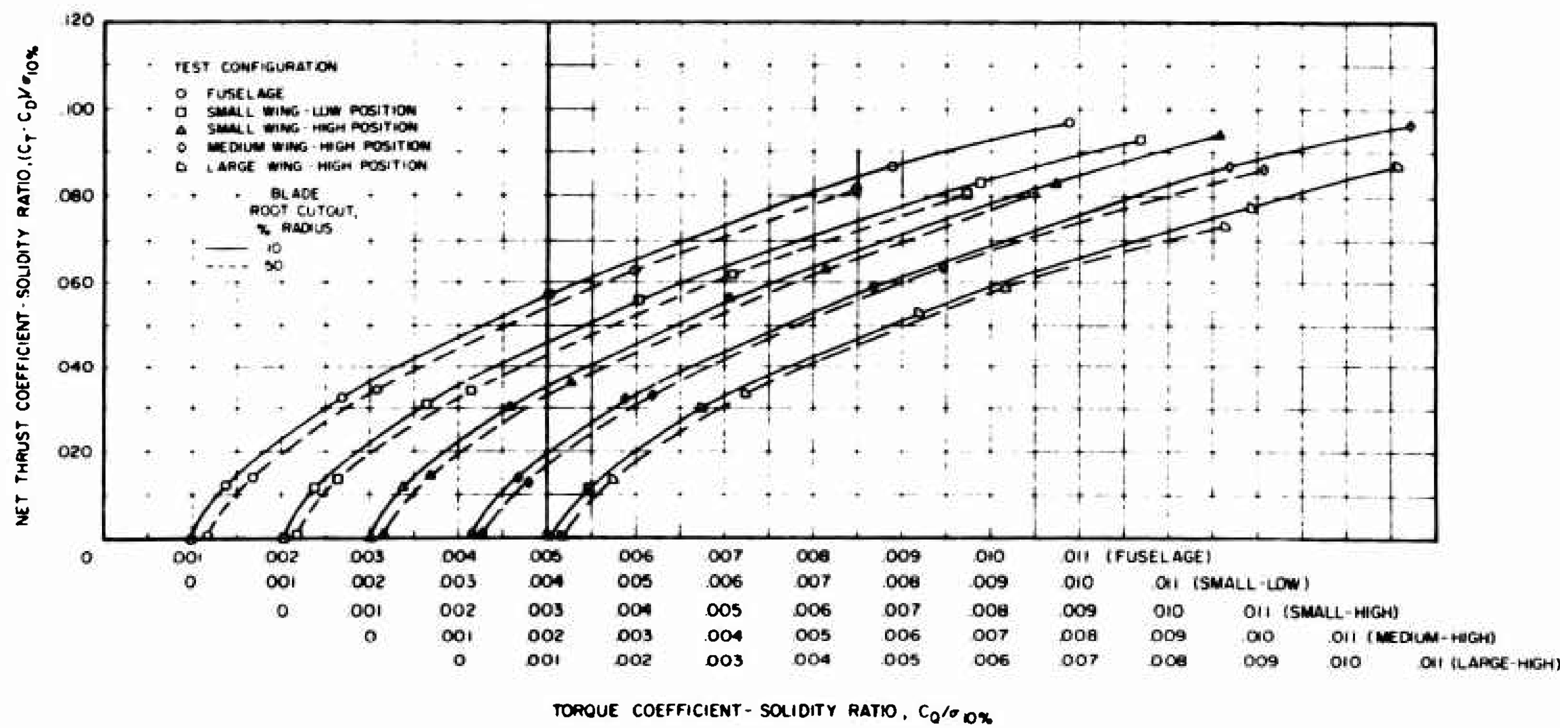


Figure 10. Variation of Rotor Torque With Net Thrust.

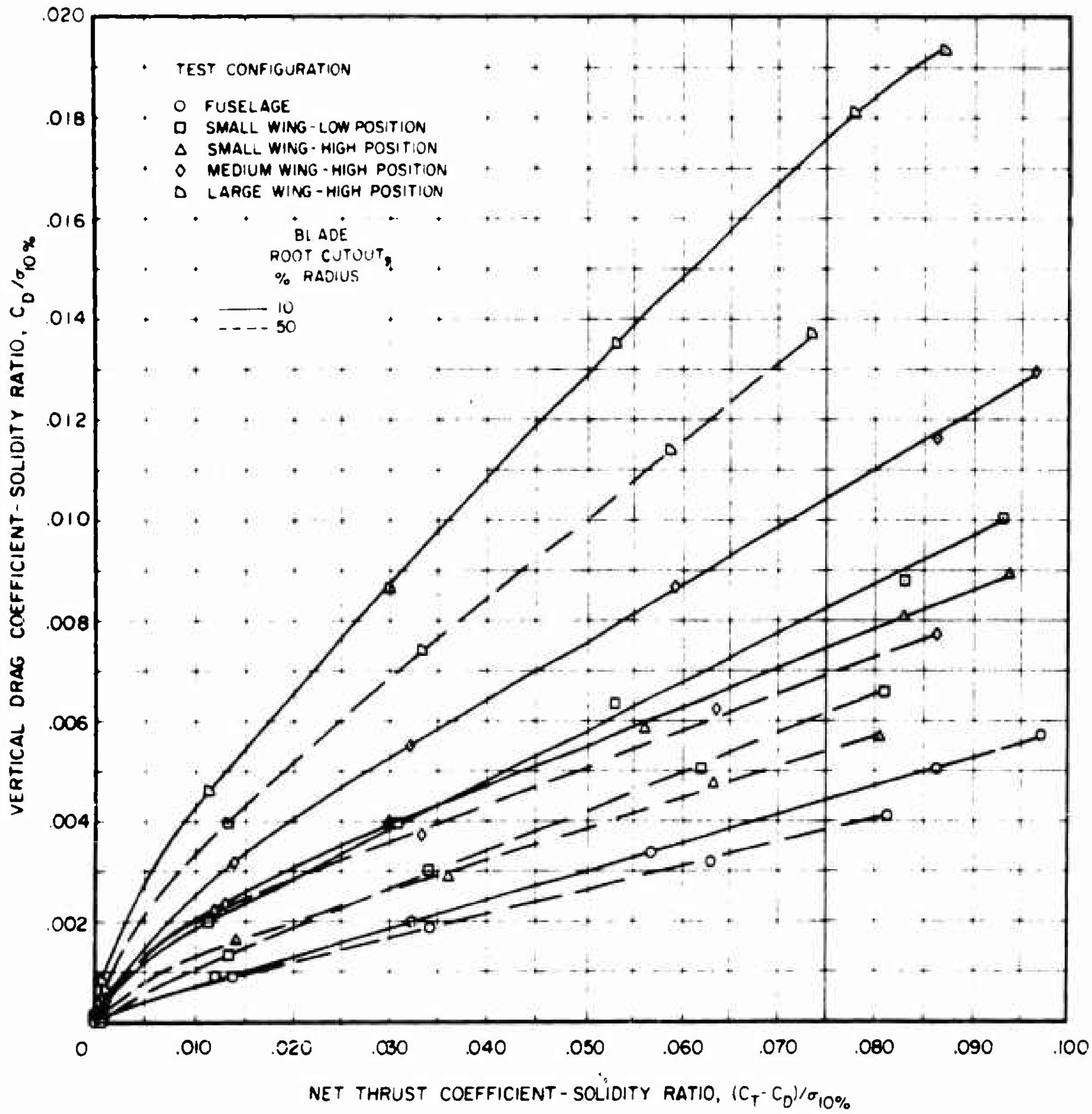


Figure 11. Variation of Airframe Vertical Drag With Net Thrust.

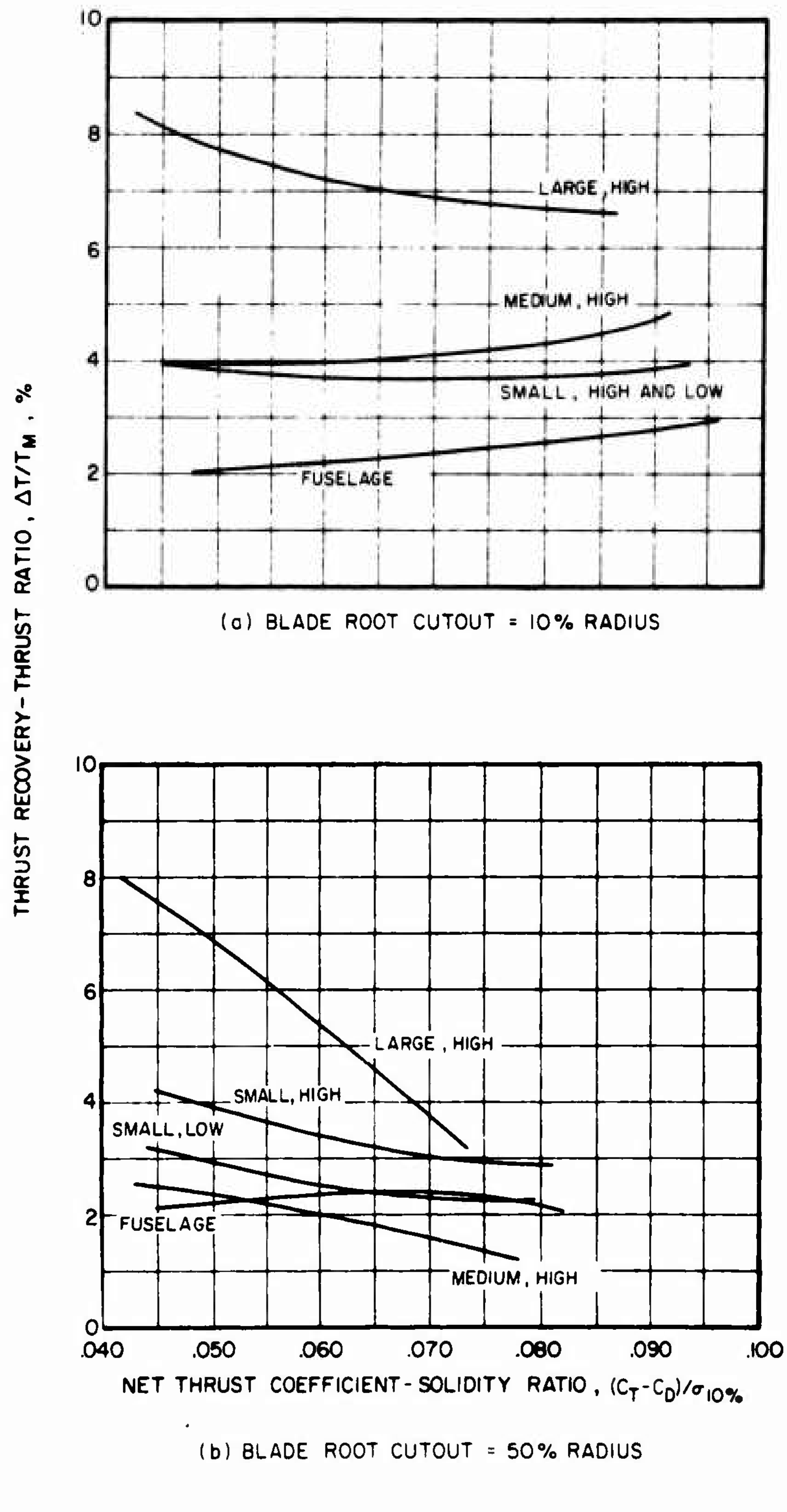


Figure 12. Variation of Thrust Recovery-Thrust Ratio With Net Thrust.

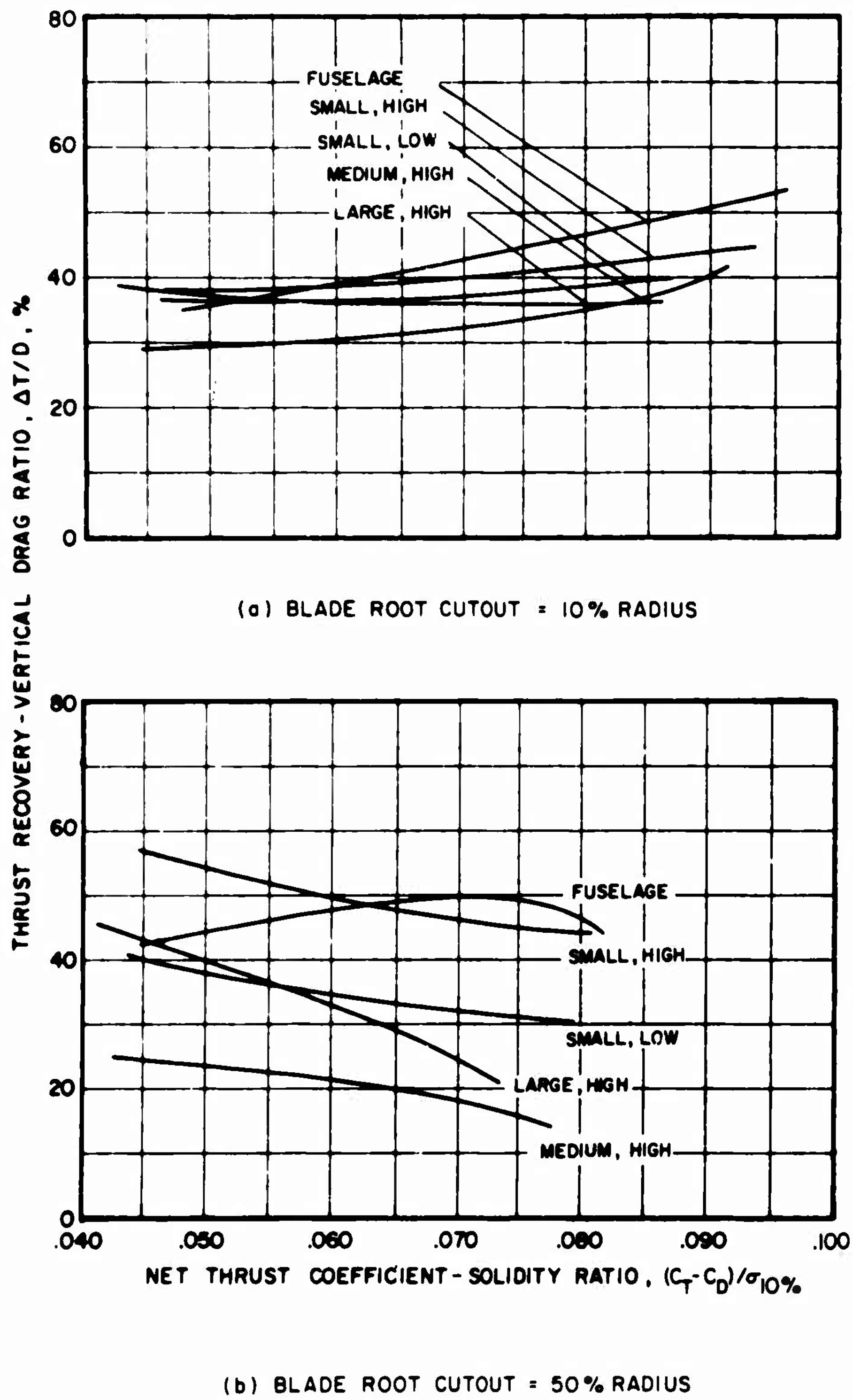


Figure 13. Variation of Thrust Recovery-Vertical Drag Ratio With Net Thrust.

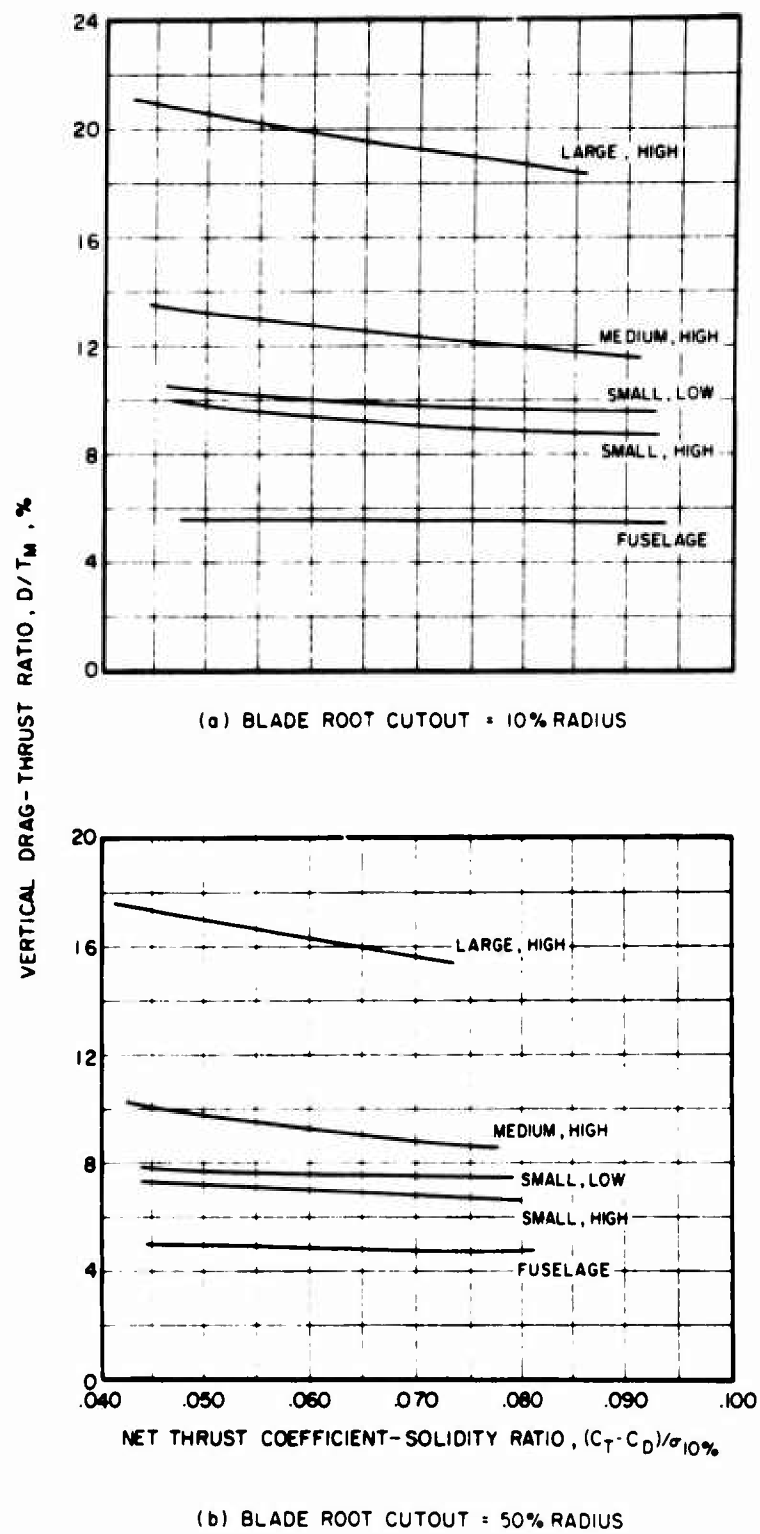
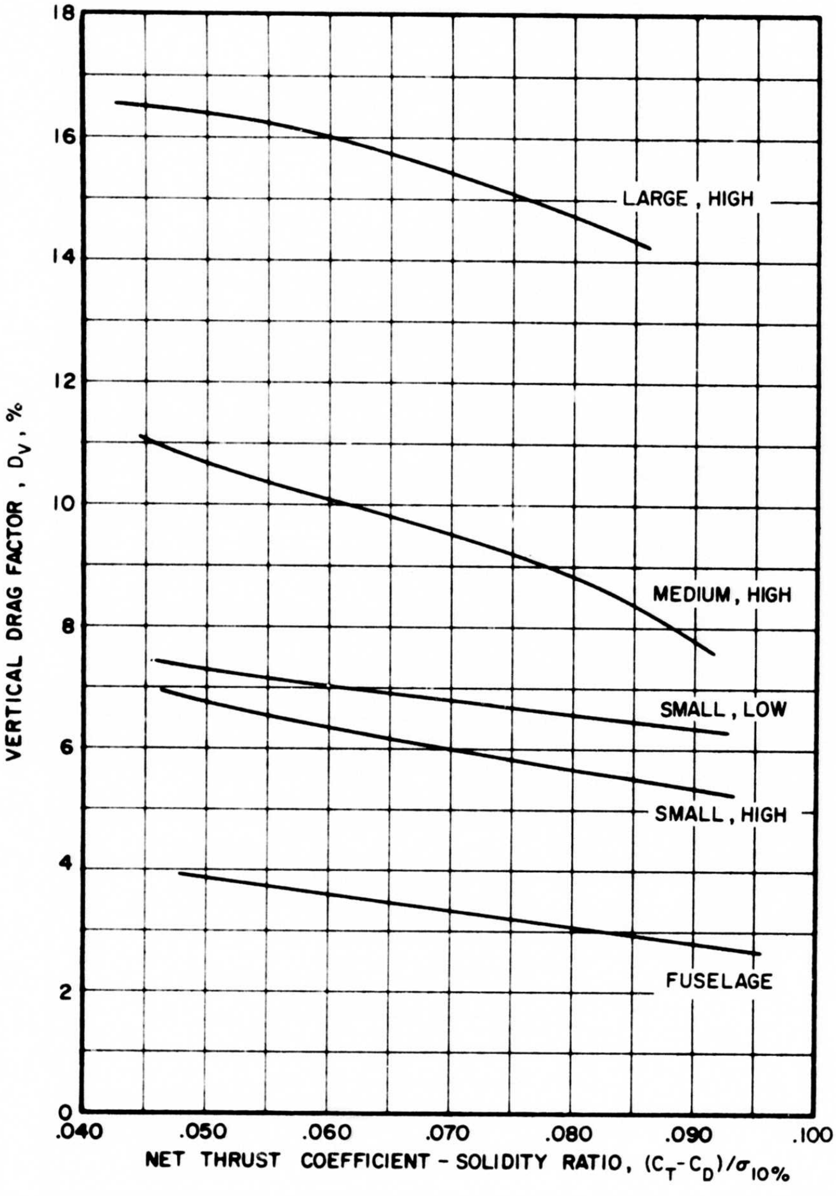
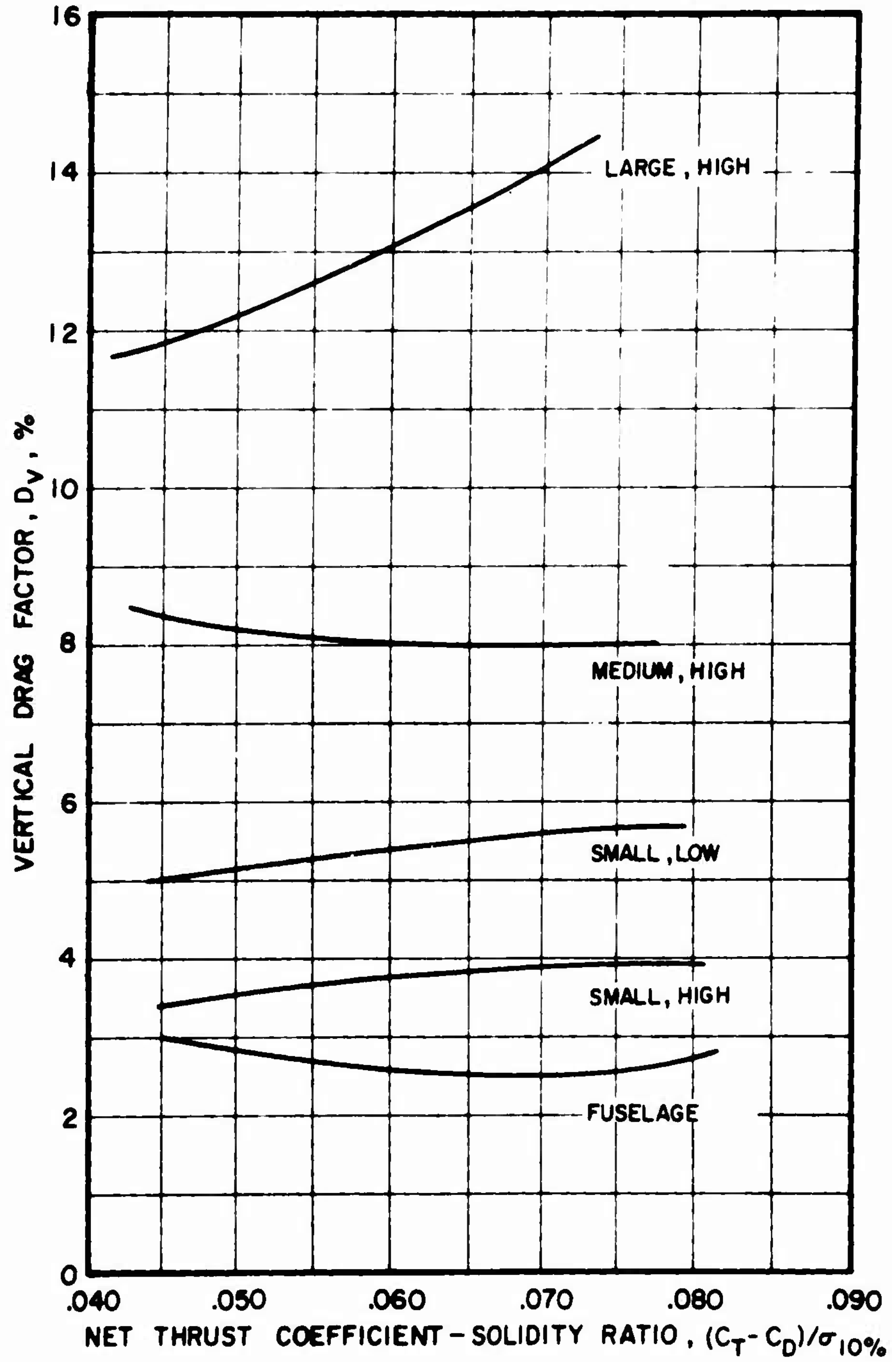


Figure 14. Variation of Vertical Drag-Thrust Ratio With Net Thrust.



(a) BLADE ROOT CUTOUT = 10% RADIUS

Figure 15. Variation of Vertical Drag Factor With Net Thrust.



(b) BLADE ROOT CUTOUT = 50% RADIUS

Figure 15. Concluded.

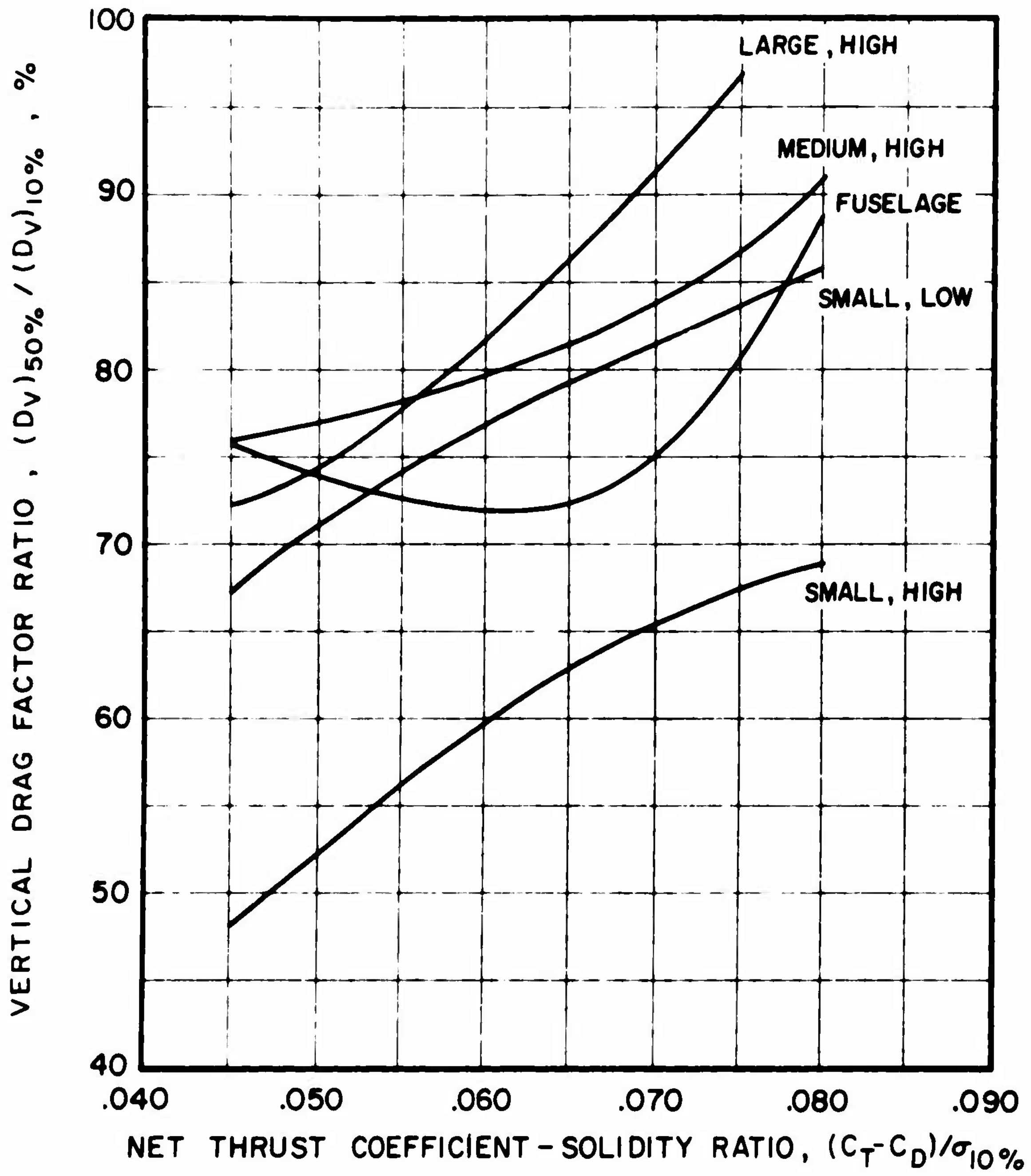
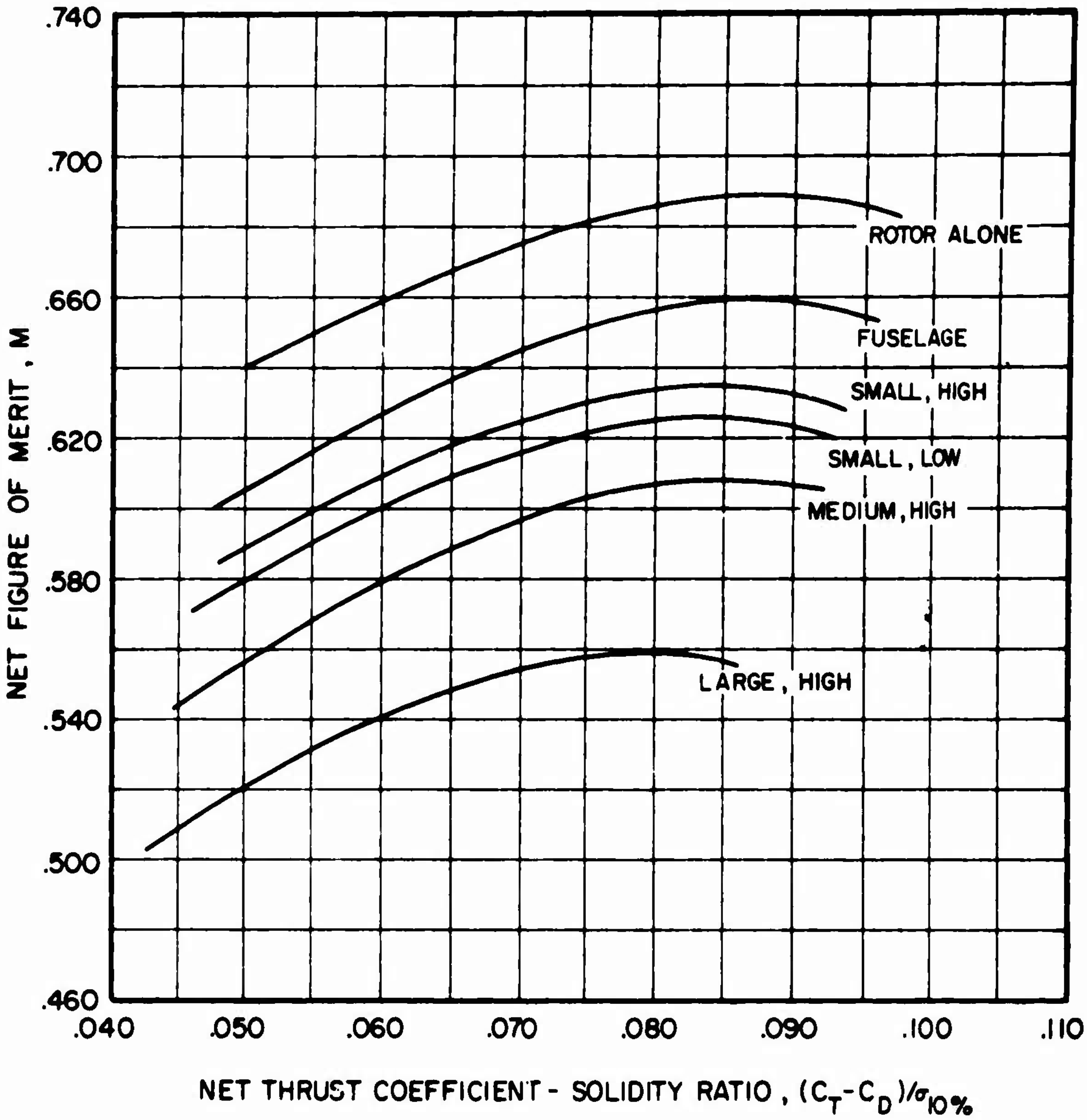
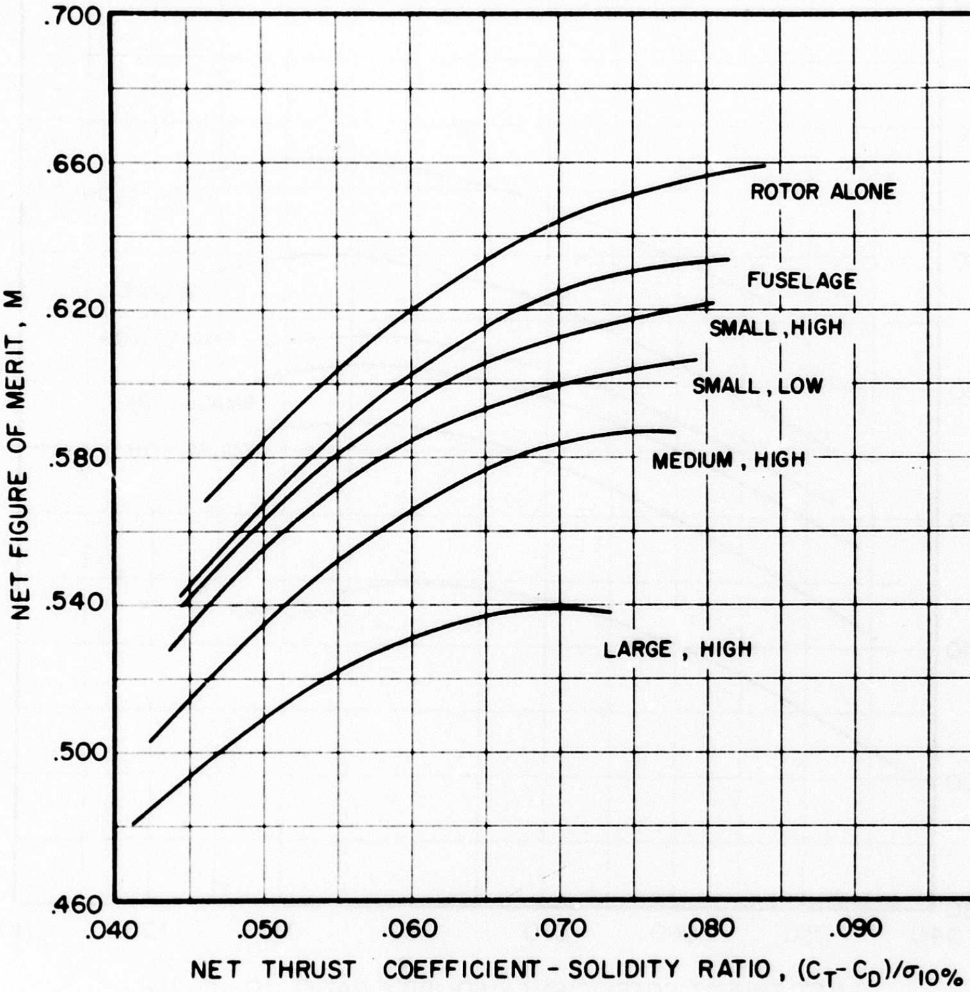


Figure 16. Reduction in Vertical Drag Factor Due to 50 Percent Blade Root Cutout.



(a) BLADE ROOT CUTOUT = 10% RADIUS

Figure 17. Variation of Net Figure of Merit With Net Thrust.



(b) BLADE ROOT CUTOUT = 50% RADIUS

Figure 17. Concluded.

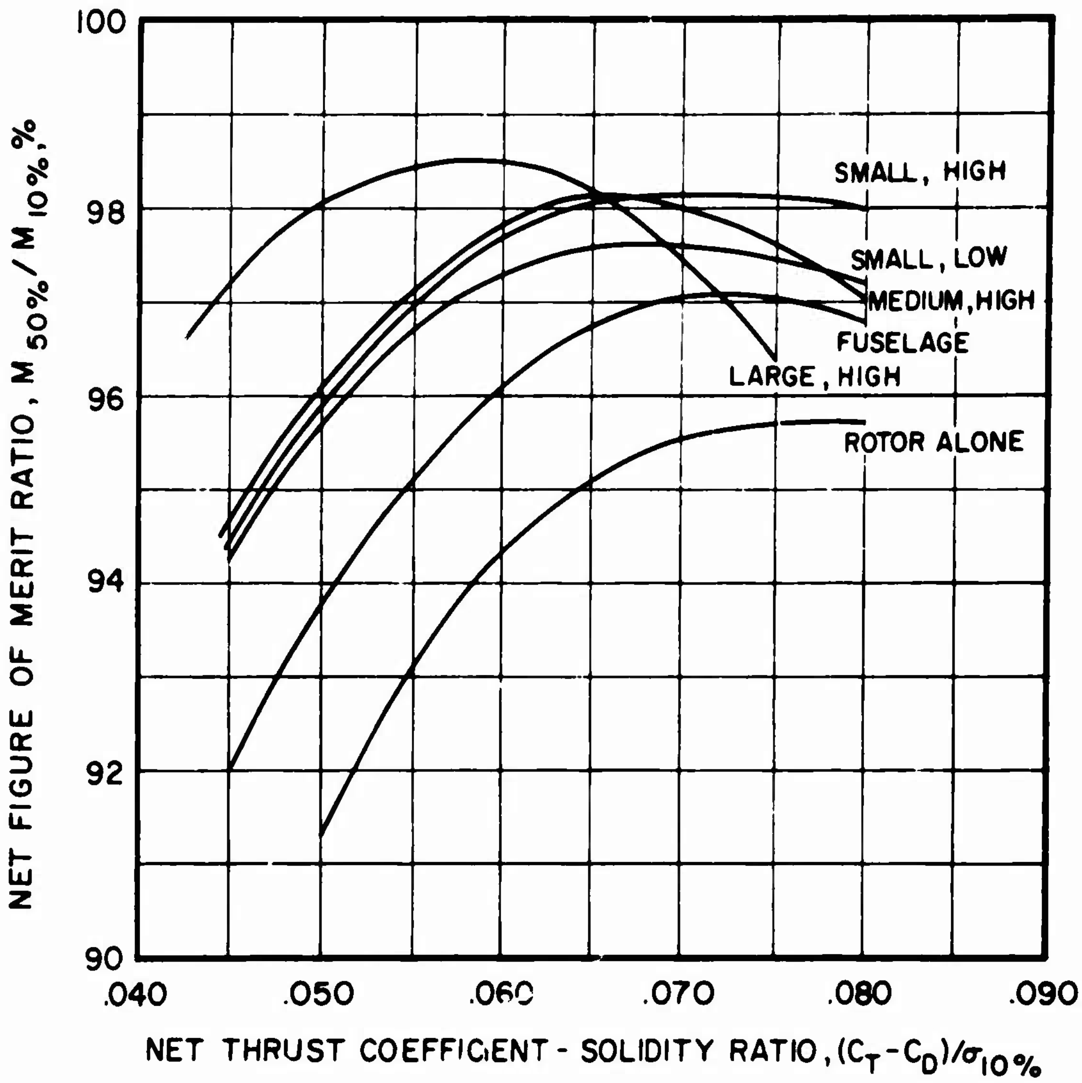


Figure 18. Effect of 50 Percent Blade Root Cutout on Figure of Merit Ratio.

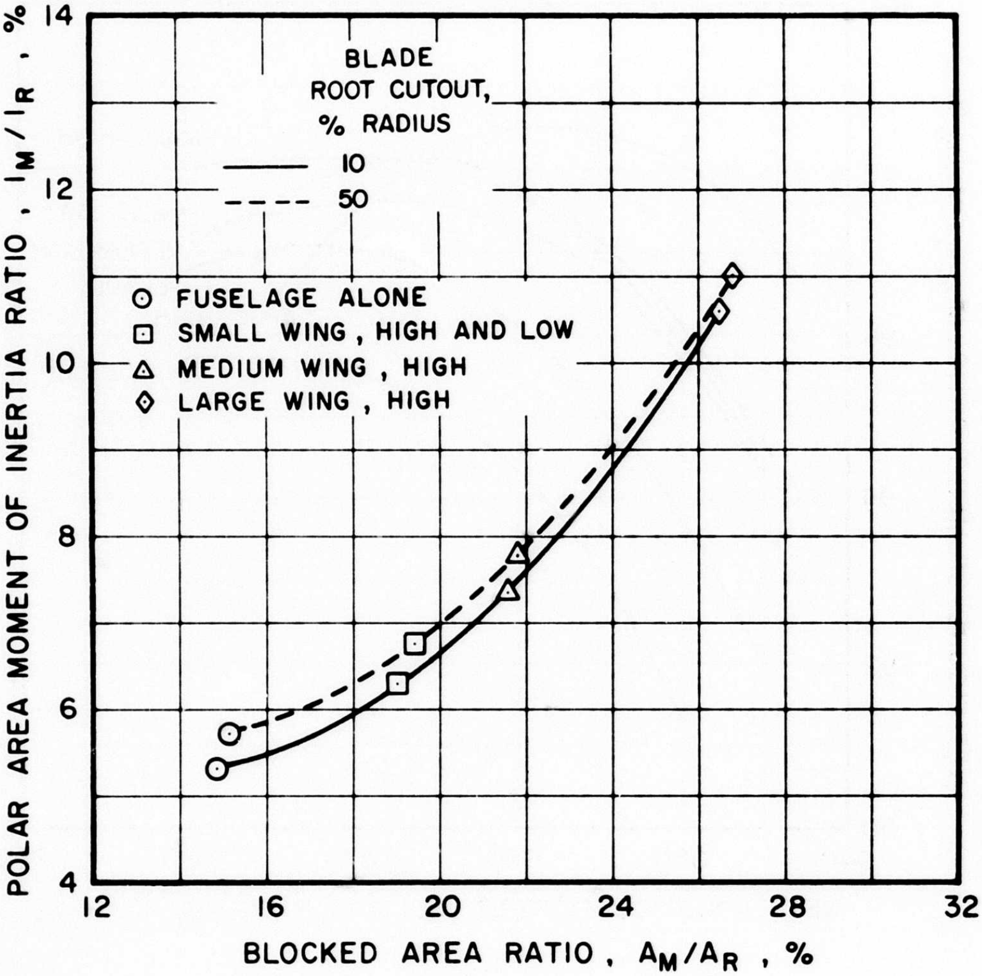


Figure 19. Blocked Area Ratio and Polar Area Moment of Inertia Ratio of Test Configurations.

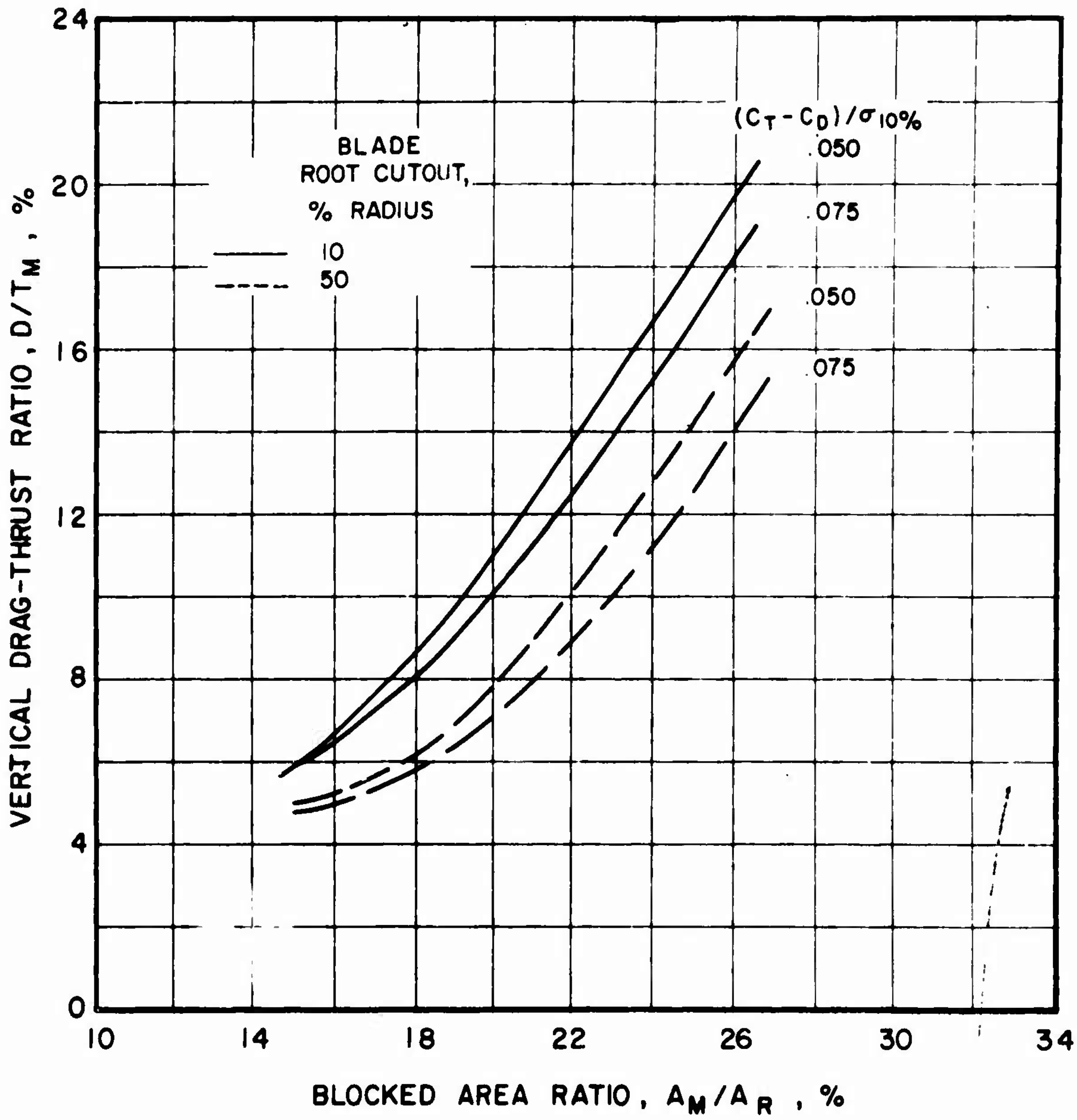


Figure 20. Correlation of Vertical Drag-Thrust Ratio With the Blocked Area Ratio.

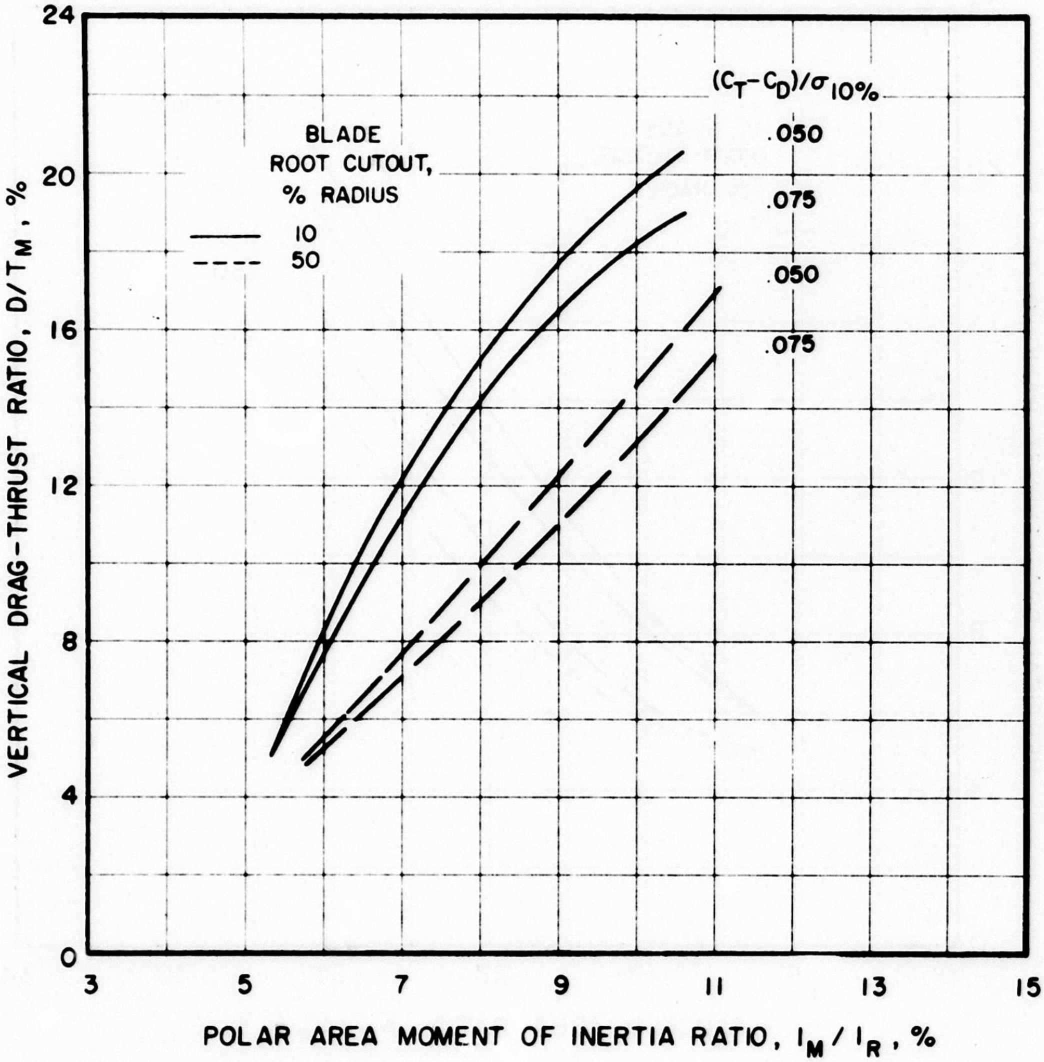


Figure 21. Correlation of Vertical Drag-Thrust Ratio With the Polar Area Moment of Inertia Ratio.

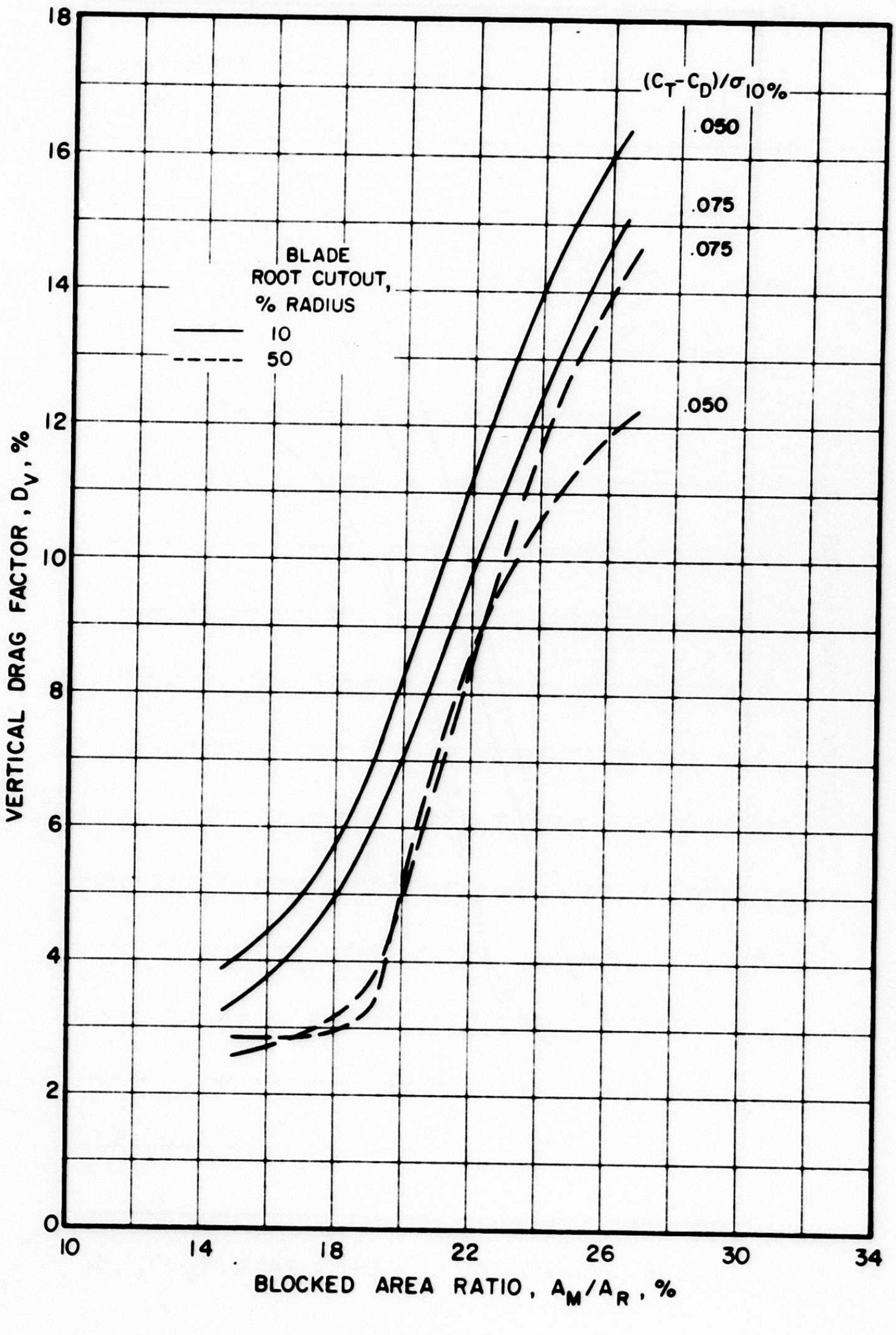


Figure 22. Correlation of Vertical Drag Factor With the Blocked Area Ratio.

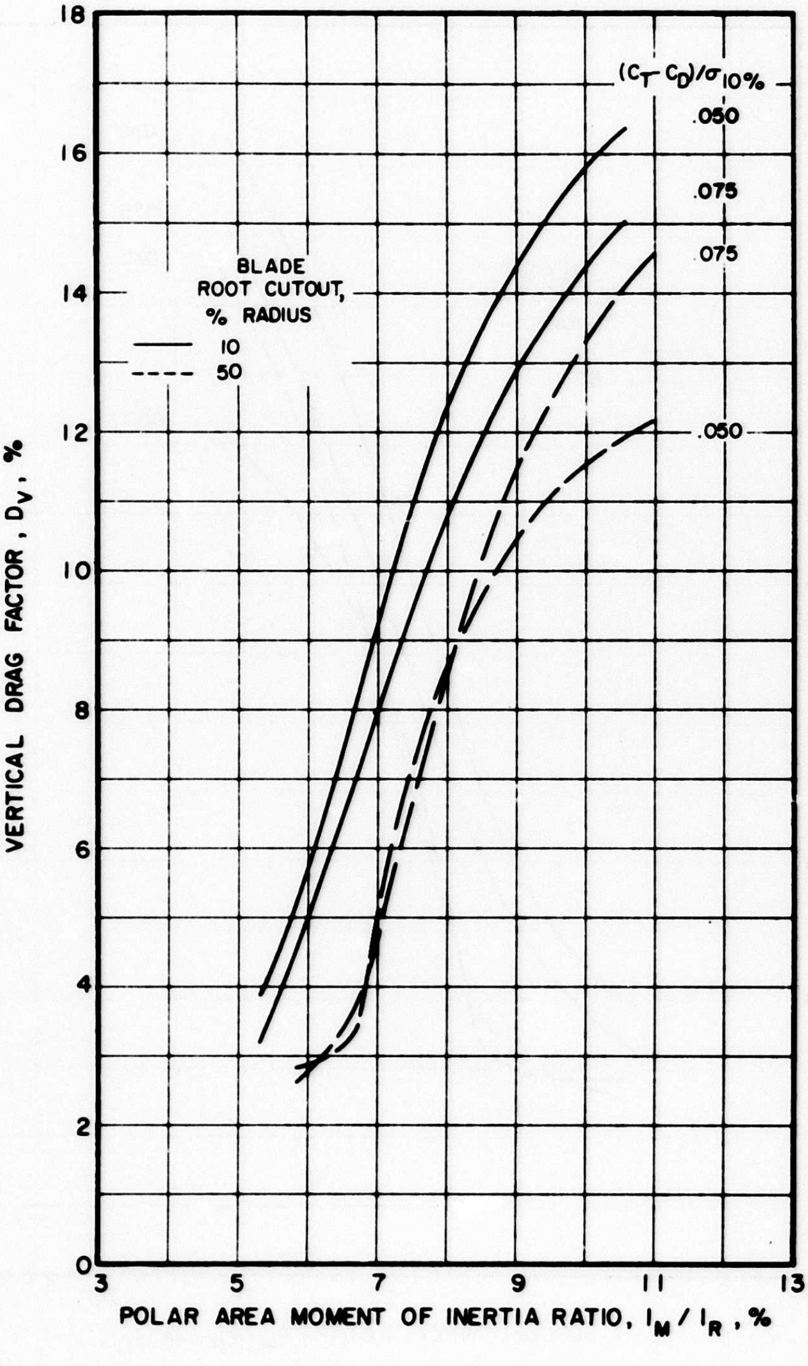


Figure 23. Correlation of Vertical Drag Factor With the Polar Area Moment of Inertia Ratio.

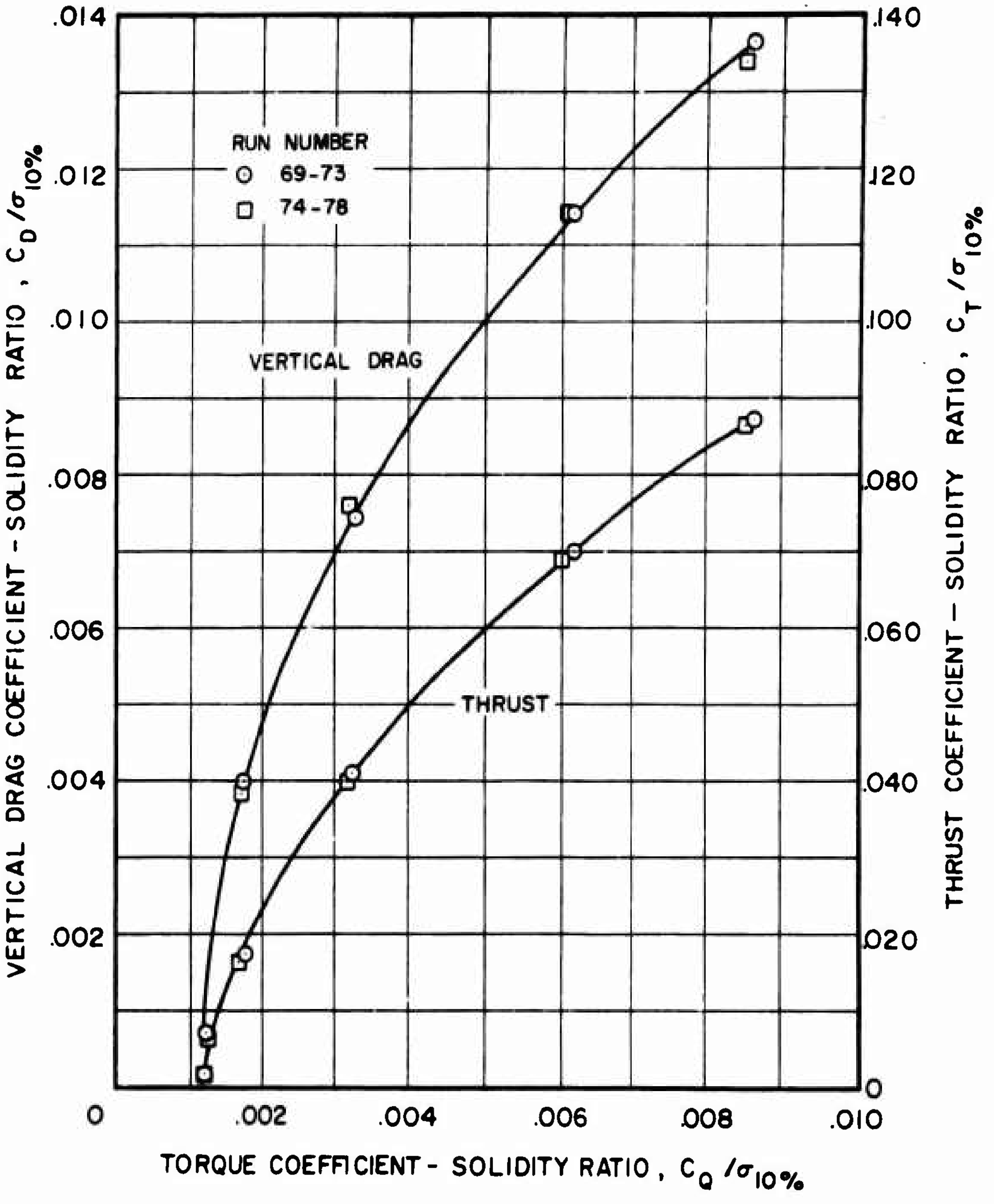


Figure 24. Test Data Repeatability for the Large Wing With the 50 Percent Root Cutout Rotor.

APPENDIX

SUMMARY OF TEST DATA RUNS

Run Number	Root Cutout (%R)	Collective Pitch (deg)	Nominal Tip Speed (ft/sec)	Model Configuration
1	10	0	700	Rotor Alone
2	10	2.5	700	
3	10	5.0	700	
4	10	7.5	700	
5	10	10.0	700	
6	10	11.0	700	
7	10	12.0	640	
8	50	0	700	
9	50	2.5	700	
10	50	5.0	700	
11	50	7.5	700	
12	50	9.0	700	
13	50	9.5	690	
14	10	0	700	Fuselage Alone
15	10	2.5	700	
16	10	5.0	700	
17	10	7.5	700	
18	10	10.0	700	
19	10	11.0	700	
20	10	12.0	640	
21	50	0	700	
22	50	2.5	700	
23	50	5.0	700	
24	50	7.5	700	
25	50	9.0	700	
26	10	0	700	Fuselage and Small Low Wing
27	10	2.5	700	
28	10	5.0	700	
29	10	7.5	700	
30	10	10.0	700	
31	10	11.0	700	
32	10	12.0	640	
33	50	0	700	
34	50	2.5	700	
35	50	5.0	700	
36	50	7.5	700	
37	50	9.0	700	

Run Number	Root Cutout (%R)	Collective Pitch (deg)	Nominal Tip Speed (ft/sec)	Model Configuration
38	10	0	700	Fuselage and Small High Wing
39	10	2.5	700	
40	10	5.0	700	
41	10	7.5	700	
42	10	10.0	700	
43	10	11.0	700	
44	10	12.0	640	
45	50	0	700	
46	50	2.5	700	
47	50	5.0	700	
48	50	7.5	700	
49	50	9.0	700	
50	10	0	700	Fuselage and Medium High Wing
51	10	2.5	700	
52	10	5.0	700	
53	10	7.5	700	
54	10	10.0	700	
55	10	11.0	700	
56	50	0	700	
57	50	2.5	700	
58	50	5.0	700	
59	50	7.5	700	
60	50	9.5	700	
61	50	10.0	680	
62	10	0	700	Fuselage and Large High Wing
63	10	2.5	700	
64	10	5.0	700	
65	10	7.5	700	
66	10	10.0	700	
67	10	11.0	700	
68	10	12.0	640	
69	50	0	700	
70	50	2.5	700	
71	50	5.0	700	
72	50	7.5	700	
73	50	9.0	700	
74*	50	0	700	
75*	50	2.5	700	
76*	50	5.0	700	
77*	50	7.5	700	
78*	50	9.0	700	

* Test data repeatability runs.

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13. ABSTRACT

Tests were conducted to determine the effect of rotor blade root cutout on the vertical drag of winged rotorcraft. Rotor thrust and torque were measured on isolated model rotors with blade root cutouts of 10 and 50 percent radius and were compared to the values obtained when a model fuselage and wings of three different planform areas were located below the rotor disc. Vertical drag was recorded on all airframe configurations with both sets of root cutout blades.

The test data revealed a decrease in vertical drag for all airframe configurations when tested with the blades having 50 percent root cutout. The largest vertical drag reduction was measured for a small wing located high on the fuselage. The 4 percent figure of merit penalty due to 50 percent blade root cutout of the isolated rotor was diminished to 2 to 3 percent for most conditions when the reduction in vertical drag was taken into consideration.

DD FORM 1 NOV 65 1473 (PAGE 1)
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14 KEY WORDS	LINK A		LINK B		LINK C	
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Rotor Hover Performance						
Rotor Blade Root Cutout						
Vertical Drag						
Vertical Drag Factor						
Rotor Thrust Recovery						
Blocked Area Ratio Correlation Method						
Polar Area Moment of Inertia Ratio Correlation Method						
Figure of Merit						
Model Rotor Hover Test						

DD FORM 1 NOV 65 1473 (BACK)
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